Restigouche River Ice Study

Ice Breakup and Jamming in the Restigouche River, New Brunswick: 1987-1988 Observations

February 1991

Environment Canada
The National Water Research Institute

Environnement Canada
L'institut national de recherche sur les eaux

New Nouveau Brunswick
Department of the Environment
Enviromental Planning and Sciences Branch

Département de l'environnement
Direction de la plannification et des sciences de l'environnement

CNB 90311

91-05178/

ICE BREAKUP AND JAMMING IN THE RESTIGOUCHE RIVER, NEW BRUNSWICK: 1987-1988 OBSERVATIONS

by

S. Beltaos[1] and B.C. Burrell[2]

[1]Research Scientist
Rivers Research Branch
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario, L7R 4A6

[2]Senior Hydrotechnical Engineer
Environmental Planning and Sciences Branch
New Brunswick Department of the Environment
Fredericton, N.B.

ABSTRACT

The Restigouche River ice study was initiated in 1987 by the Federal and New Brunswick Departments of the Environment, in order to investigate breakup and jamming processes in a stream of considerable size and slope. Moreover, the Restigouche is subject to the relatively severe winter conditions of Northern New Brunswick which are also typical of many other regions of Canada. Ice jams are known to occur frequently along the Restigouche and to cause serious flooding.

The study focuses on breakup processes but freeze up and winter conditions are also being monitored because of their potential influence on the severity of the breakup. Emphasis is on collection of qualitative and quantitative field data that can be used to develop or improve predictive models. To sample an adequate range of the variable hydro-meteorologic conditions, several breakup events need to be documented and studied.

This report presents the first year's observations and data, along with the associated analysis and interpretation. The 1988 breakup event was of the mechanical type, accompanied by considerable jamming and some flooding of low-lying areas. Most notably, an ice jam formed upstream of Mann Mountain settlement, lasting for over three days. Its configuration near the toe, or downstream end, was documented in detail and it was found that extensive grounding occurred locally, a condition often suspected in the past but not demonstrated by measurement. The ice jam water levels and thicknesses were compared with theoretical predictions, using the recently developed model RIVJAM. With plausible values for the various model

coefficients, it was possible to approximately reproduce the measured configuration of the jam. One exception was the coefficient expressing the intensity of flow through the voids of the jam: it appears to be too high relative to what is expected from laboratory data. More case studies are needed to elucidate this question. The release of the jam was, in an unknown manner, related to the formation and gradual expansion of an open lead that developed at the toe. Further study of this phenomenon is needed.

RÉSUMÉ

L'étude des glaces de la rivière Restigouche a été entreprise en 1987 par les ministères de l'Environnement fédéral et du Nouveau-Brunswick afin d'étudier les débâcles et les embâcles dans un cours d'eau ayant une dimension et une pente de ligne d'eau considérables. La Restigouche est aussi assujettie aux conditions hivernales relativement rigoureuses du Nord du Nouveau-Brunswick qui sont également typiques de bon nombre d'autres régions du Canada. Il se produit souvent des embâcles qui causent de graves inondations le long de la Restigouche.

L'étude met l'accent sur la débâcle mais le gel et les conditions hivernales sont également surveillés en raison de l'influence qu'ils pourraient avoir sur la gravité de la débâcle. L'accent est mis sur la collecte sur place de données quantitatives et qualitatives pouvant servir à établir ou à améliorer des modèles de prévision. Pour obtenir un échantillonnage adéquat des conditions hydrologiques et météorologiques variables, il faut documenter et étudier plusieurs débâcles.

Ce rapport présente les observations et les données de la première année ainsi que l'analyse et l'interprétation connexes. La débâcle de 1988 a été d'ordre mécanique; elle a été suivie de graves embâcles et d'inondations dans les basses régions. Qui plus est, il s'est créé, en amont de Mann Mountain settlement, un embâcle qui a duré plus de trois jours. Sa configuration près de l'extrémité d'aval, a été documentée en détail et on a constaté beaucoup d'échouage local, un phénomène souvent soupçonné par le

passé mais non démontré par des mesures scientifiques. Les niveaux de l'eau et les épaisseurs de l'embâcle ont été comparés aux prévisions théoriques, à l'aide du modèle RIVJAM mis au point récemment. Au moyen de valeurs plausibles pour les divers coefficients de modèle, on a pu reproduire de façon approximative la configuration mesurée de l'embâcle. Il y avait cependant une exception, le coefficient exprimant l'intensité du débit à travers les vides de l'embâcle : il semblait trop élevé par rapport à ce que laissaient prévoir les données de laboratoire. Il faut effectuer d'autres études de cas pour éclaircir cette question. La rupture de l'embâcle a été de façon inconnue reliée à la formation et à l'expansion progressive d'un chenal libre qui s'est créé à l'extrémité d'aval. Ce phénomène mérite d'être étudié davantage.

MANAGEMENT PERSPECTIVE

Ice jams are a major cause of flooding and related problems in Canada but an engineering capability to predict and mitigate such problems is limited because of lack of knowledge regarding river ice processes. Study of such processes in the field is a practical research approach, given the many difficulties associated with reproducing them in the laboratory.

The Restigouche River ice study is a research project on ice breakup and jamming, carried out jointly by the National Water Research Institute of Environment Canada and the Environmental Planning and Sciences Branch of New Brunswick Environment. The Restigouche River, having considerable size and slope, and being subject to the relatively severe winters of Northern New Brunswick, has a very different ice regime from that of previously studied streams in southern parts of New Brunswick and Ontario. Essentially, the study consists of documenting several ice breakup events so as to "sample" an adequate range of hydrologic and climatic conditions. The focus is on obtaining data that can be used to improve or develop predictive models.

This report presents the results of the first year's observations, along with a quantitative analysis and interpretation. Using the measurements obtained during the 1988 event, a successful application was made of the numerical model RIVJAM, developed recently at the National Water Research Institute to compute the configuration and water levels of ice jams. Several questions that need further study were identified, most importantly pertaining to the flow through the voids of an ice jam and to the factors governing its release.

PERSPECTIVE - GESTION

Les embâcles sont une cause principale des inondations et des problèmes connexes au Canada, mais la capacité technique de prédire et de réduire ces problèmes est limitée en raison du manque de connaissance concernant les processus des glaces fluviales. L'étude sur place de ces processus est une méthode de recherche pratique, vu les nombreuses difficultés liées à leur reproduction en laboratoire.

L'étude des glaces de la rivière Restigouche est un projet de recherche sur les embâcles et les débâcles entrepris conjointement par l'Institut national de recherche sur les eaux d'Environnement Canada et la Direction de la planification et des sciences de l'environnement du ministère de l'Environnement du Nouveau-Brunswick. La rivière Restigouche a une dimension et une pente de ligne d'eau considérables; elle est assujettie aux conditions hivernales relativement rigoureuses du Nord du Nouveau-Brunswick et elle a un régime de glaces très différent de celui des cours d'eau déjà étudiés dans le Sud du Nouveau-Brunswick et de l'Ontario. Essentiellement, l'étude consiste à documenter plusieurs débâcles de façon à obtenir un échantillonnage adéquat des conditions hydrologiques et climatiques. L'accent est mis sur l'obtention de données pouvant servir à améliorer ou à établir des modèles de prévision.

Ce rapport présente les résultats des observations de la première année, ainsi qu'une analyse et une interprétation quantitatives. À l'aide des mesures obtenues durant la débâcle de

1988, on a appliqué avec succès le modèle numérique RIVJAM, mis au point récemment à l'Institut national de recherche sur les eaux pour calculer la configuration et les niveaux d'eau des embâcles. On a identifié plusieurs questions qui ont besoin d'être étudiées davantage, dont la plus importante concerne le débit dans les vides d'un embâcle et les facteurs régissant sa rupture.

TABLE OF CONTENTS

	PAGE
INTRODUCTION	1
STUDY REACH	3
FREEZE UP AND WINTER 1987-88	6
BREAKUP 1988	7
March 31	7
April 2	7
April 4	8
April 5	8
April 6	9
April 7	10
April 8	11
April 9	12
April 10	14
April 11	15
April 12	15
HYDROMETRIC DATA	15
Ice Thickness	15
Discharge	15
Hydraulic Data	18
DATA ANALYSIS AND INTERPRETATION	19
Initiation of Breakup	19
Ice Jam Profiles	20
DISCUSSION	23
SUMMARY AND CONCLUSIONS	24
ACKNOWLEDGMENTS	26
REFERENCES	27
TABLE	
FIGURES	
PHOTOGRAPHS	

INTRODUCTION

River ice processes are an integral part of the regime of northern rivers and occasionally have considerable impact on riverside communities and nearby structures. Most of the impact is caused by ice jams that form during the freeze up and (more importantly) during the breakup periods. In the past, ice jams have been considered beyond prediction and amenable to little human influence and control. This situation has been improved by research in the past three decades so that ice effects can be partly considered in river management schemes and various hydrotechnical studies.

A major component of river ice research relies on field studies because of the many difficulties associated with laboratory simulation of the complex hydraulic, thermal and structural processes involved. To obtain quantitative and qualitative field data with which to test and enhance existing understanding, systematic annual breakup documentation was initiated in 1988 along the Restigouche River, New Brunswick.

In the early eighties, the National Water Research Institute carried out field programs on two Southwestern Ontario rivers, the Thames and the Grand. As a result, the regional ice regime is fairly well understood (e.g. see Beltaos, 1987 and Wong and Beltaos, 1986). Rivers in Southwestern Ontario are relatively small and often experience two or three breakup events in any one year owing to "winter thaws" associated with rainfall, typical of this region's climate. The increased runoff is often sufficient to dislodge and break the ice cover thus resulting in what is known as "premature" breakup. Such events can be very damaging because the associated ice jams are the most persistent as they are held in place by sections of

intact ice cover that retains most of its strength. On the other hand, the relatively small size of Southwestern Ontario rivers has a moderating effect because the attendant ice jams are not as thick and create lesser backwater than those in large streams. Similar considerations apply to previous studies of Southern New Brunswick rivers (e.g. see Beltaos, 1984; Tang et al., 1986; Prowse et al., 1989).

The Restigouche River, is, on the other hand, more representative of northern Canadian conditions, i.e. large streams subjected to a single breakup event each year. Premature events are possible but not as frequent as in lower latitudes. The stream size, though moderate by comparison to that of the Mackenzie or the Peace, combines with its considerable slope to produce very thick ice jams and serious flooding. Thus the Restigouche was selected for a joint study by the National Water Research Institute (abbreviated to NWRI herein) and the New Brunswick Department of the Environment (abbreviated to NBDOE).

In addition to the specific interests of the above mentioned agencies, the Restigouche study also addresses some of the objectives of the Flood Damage Reduction Program and of the N.B. Sub-committee on River Ice. Though the study focuses on the breakup processes, freeze up and winter conditions are regularly monitored because of their influence on breakup. Emphasis is on collection of quantitative data that can be used to develop or calibrate predictive models.

This report presents the results of the first year's observations. An analysis of historical information has also been carried out and will be presented in a separate report. Additional background information and discussion of the field program are provided by Beltaos and Burrell (1990b).

STUDY REACH

The Restigouche River originates in the Chaleur Uplands and flows into Chaleur Bay at Dalhousie. The main tributaries are the Matapedia, Patapedia, Kedgwick, and Upsalquitch rivers. The latter rises in the New Brunswick Highlands while the former three rise in the Notre Dame mountains of Quebec. From its junction with the Patapedia River and downstream, the Restigouche forms the boundary between Quebec and New Brunswick (Fig. 1). The lower reach of the river is subject to tidal influences while a little farther upstream it flows in multiple channels around many islands (Fig. 2c). To avoid the complexities associated with such conditions, the study reach extends upstream of the community of Flatlands (Fig. 2b). The upper limit of the study reach, Wyer's Brook, is imposed by accessibility constraints (Fig 2a). Upstream of Wyer's Brook, observations are only qualitative and carried out from chartered fixed wing aircraft. The Upsalquitch and Matapedia Rivers (Figs. 2d, 2e) are also monitored, mainly to determine their effects on the breakup of the Restigouche.

Ice jams are known to form throughout the study reach and particularly near the town of Matapedia, situated by the mouth of the Matapedia River. An extensive study of possible remedial measures has been carried out by the Quebec Ministry of Natural Resources (Gidas, 1979, 1981). Farther downstream, several communities on the New Brunswick side have experienced similar problems, e.g., Flatlands, Tide Head, Atholville, and Campbellton (Leger, 1986). Figure 3 is an approximate longitudinal profile of the river based on existing topographic maps. The origin of river distance (measured upstream) has been arbitrarily fixed at Old Mission Point, Atholville. Figure 4

illustrates selected river cross-sections in the study reach, surveyed during open-water conditions in 1988, 1989 and 1990. The locations of these sections are shown in Fig. 2, where the sections are designated by their river distance, in kilometres, upstream of Old Mission Point. A total of 42 cross-sections have been surveyed to date, and are usually congregated in areas where ice jams have been documented during the respective breakup events.

The farthest downstream Water Survey of Canada (WSC) gauge is located near the mouth of Rafting Ground Brook (RGB). Here, the drainage area is 7740 square kilometres. The long-term average discharge is 165 m^3/s which translates to local width and depth of 140 m and 1.4 m., respectively, under open water conditions. The presence of the gauge in the study reach is advantageous because it provides important hydrometric data and shelter for meteorologic instruments, installed specifically for this study.

For open water conditions, reach - average hydraulics in the vicinity of the gauge (slope = 0.00082) is summarized in Table I. From the discharge rating tables provided by Water Survey of Canada, the following equation has been developed:

$$Q = 180\ (H - H_0)^{1.70} \qquad \text{[open water]} \qquad (1)$$

in which Q = flow discharge in m^3/s; H = gauge height in metres; H_0 = 0.30 m. Note that the geodetic elevation of zero H is 14.04 m.

Analysis of existing gauge records (1969-87) indicated that the lower Restigouche typically freezes in December and breaks up in April. Spring runoff usually results from both rainfall and snowmelt

and is a major factor contributing to the flooding potential of the breakup (Figs. 5 and 6). The ice cover initially consists of a slush accumulation, 1 m - 3 m thick. As the winter progresses, a layer of solid ice grows downward from the water surface into the porous slush while the bottom of the slush recedes upward by thermal erosion. Past hydrometric measurements (WSC records) indicate that the slush disappears by early April. Figure 7 shows the thickness of the solid ice cover plotted against the number of days since freeze up, a parameter found to be a better predictor than the degree days of freezing. It is noted that Fig. 7 is based on thicknesses measured near the Rafting Ground Brook gauge and does not necessarily provide information that applies to the entire study reach.

For forecasting and modelling purposes, it is important to know the ice thickness at the "end of winter", i.e. when a net gain of heat begins to be experienced by the ice. This thickness can be estimated by extrapolation if a few measurements are taken during the winter months. Following Bilello (1980), the end of winter is herein defined as the time when the air temperature rises consistently above -5°C.

Another important parameter is flow discharge; it is difficult to obtain because measurements are not possible during the breakup period and estimates require knowledge of prevailing ice conditions. A useful computation is to synthesize a rating curve for the flow under the still-intact ice cover shortly before breakup. This was done using a value of 0.02 for the Manning coefficient of the ice, along with bed resistance characteristics obtained from the open-water surveys. The resulting relationship can be described by:

$$Q = 104\,[(H - h_i') - H_0]^{1.77} \qquad \text{[sheet ice cover]} \qquad (2)$$

in which h_i' is the submerged thickness of the cover in metres.

Equation 2 has been checked against published data and found reliable to within 25 percent; in Fig. 5, it is seen to adequately describe the "low" events which involve no jamming but merely thermal disintegration of the ice cover.

Typically, breakup follows an initial rise and plateau of the water level hydrograph (Fig. 8) and lasts for several days until the ice is cleared and its effect on stage becomes negligible. The initial slow rise in Fig. 8 is caused by mild temperatures and moderate rainfall while the "plateau" could last for a week or more. If more rain occurs during this time, a mechanical breakup event results with potential for major jamming; if no rain falls during the "plateau", the breakup is thermal and has no repercussions.

FREEZE UP AND WINTER 1987-88

The gauge recorder chart for Rafting Ground Brook (Fig. 9) indicates that freeze up occurred during December 22 - 24. As the cover progressed upstream towards RGB, the stage rose from 1.0 m to 2.5 m and "settled down" to 2.0 m which is the value taken as the "freeze up level", H_F.

Discharge and ice thickness were measured on January 27 and on March 1 and the cross-sectional configuration of the ice cover is shown in Fig. 10. Solid ice thicknesses are plotted in Fig. 7.

Periodic reconnaissance of the study reach began on February 10. On that day, the river was completely frozen over except for (a) 1 m x 30 m lead below the Upsalquitch mouth; (b) small lead below RGB, a

usual occurrence throughout the winter; and (c) 2 m x 15 m lead at the tip of Adam's Island. By February 23, the first and third leads had lengthened to 100 m and 60 m, respectively (without widening) while a new lead had appeared at the tail of Greens Island. By March 28, this lead was 5 m wide and 120 m long while other leads had also enlarged.

BREAKUP 1988

According to the -5°C criterion, the end of winter was the 23rd of March which implies that the degree-days of thaw, calculated above a base of air temperature of -5°C, remained positive after this date. A total of 19.8 mm of rain fell during March 25 - 27. Along with milder temperatures, the rain caused the river to rise from a winter low gauge height of 1.4 m to a plateau of 2.2 m that lasted between March 29 and April 3. More rain (13.4 mm) fell during April 2-4 and this led to breakup. A day-by-day chronology follows.

March 31

Ice starting to break slightly near Wyer's Brook while the lead below Greens Island extends to the mouth of the Upsalquitch where two more leads have appeared. Leads are also opening at the mouth of the Matapedia and near the Railway and Highway bridges.

April 2

Similar conditions as on March 31; little change.

April 4

Very early in the morning, the Upsalquitch ice ran and pushed 150 m into the Restigouche. At RGB, the Restigouche ice ran during 1630 - 1700 which can be taken as the onset of breakup at this site.

April 5

0600-1100: A jam has developed, extending from Grog Is. to Camp Harmony (Fig. 2) and, as a result, the road to Wyer's Brook is flooded. A shorter jam in the Upsalquitch R. is held in place by the Restigouche jam. More open leads developing in the Restigouche.

1300-2000: It was reported that the ice ran for 2.5 h (1300-1530) at Indian House Camp, some 50 km upstream. The Upsalquitch jam lengthened to 500 m below Robisonville and some cottages were flooded - see photos 1 & 2.

At 1645, the Restigouche jam released. For a few kilometres downstream of the moving rubble, the sheet ice was cracked and also moving, though its speed decreased in the downstream direction. The differential rate of advance of individual ice slabs, formed by the cracking, resulted in pressure ridges. The movement stopped at 1720 and a new jam formed with its toe located about 300 m upstream of Babcock Brook, about 2 km from its former position. Note that "toe" is the site where the broken ice of the jam meets the relatively intact sheet ice cover that usually holds the jam in place. Downstream of the toe, pressure ridges were present, diminishing in frequency and height and disappearing by 1.5 km below the toe (Photos

4 - 8). The head (upstream end) of the jam was initially 150 m upstream of the gauge but consolidated to 50 m downstream during 1940-2000.

While no flooding occured, the low section of the N.B. river road was not much above the jam level (photo 9). For later reference and survey, a set of "water level" photos were taken; these are views of the ice or water level against identifiable objects on the river banks. Under favourable conditions, the water level can be determined to within a few centimetres.

April 6

0600-1200: It was reported that the ice ran near Wyer's Brook at a speed of 20 km/h (5.6 m/s), at about 0630. This suggests that a surge went by, most likely caused by the release of an ice jam farther upstream. No significant changes were seen in the ice cover downstream of yesterday's jam except for general enlargement of the open leads. At the toe of the jam, a small lead had developed in the sheet ice cover (photos 10 & 19). This feature is typical of ice jams in large streams. About 400 m above the toe, ice blocks were on the road surface (photo 11) which was flooded 200 m farther upstream. High water marks were visible, about 0.6 m above the prevailing water level, likely a result of the surge mentioned earlier. Photo 12 shows an ice pile near the toe and photo 13 shows flooding of the New Brunswick river road.

1200-1300: The river was observed from a small aircraft and the jam was found to be 18 km long, from the toe at 300 m above Babcock Brook

to the head at 2.3 km upstream of Brandy Brook. Open water prevailed above the jam, at least as far as the Patapedia river some 55 km from the toe. High shear walls were evident all along this reach, indicating previous jamming and ice running. Both the Matapedia and Patapedia rivers were ice covered. Photos 14 - 26 are aerial views obtained during the flight.

1300-2000: No significant changes occurred during this time. The water level profile near the toe was surveyed and is plotted in Fig. 11, along with similar data obtained on April 7 and 8. Also shown are water levels obtained from the April 5 photos for comparison, even though they are not nearly as accurate as the surveyed ones. Noteworthy is the abrupt drop in the water level within the last 100 m of the jam, suggesting major blockage of the flow at the toe. The near-coincidence of the April 6-8 data points suggests a steady-state condition, i.e. approximate constancy of discharge and of ice jam configuration.

April 7

At about 0730, the ice jam consolidated near Wyer's Brook, thus dividing into two jams separated by a short section of open water. The lead at the toe had enlarged and extended into the ice rubble as well (photo 27). The water in the lead was "boiling" while ice blocks from the jam moved infrequently in the lead. At the Matapedia confluence, severe deterioration of the ice was evident. The Restigouche was partly open between the confluence and the railway bridge and fully open between this bridge and the highway bridge. Low sections of the river roads on both banks remained flooded (Ph. 28).

April 8

0700-1200: The open water section between the two jams near Wyer's Brook was 400 m long. The lead at the toe of the downstream jam had elongated considerably (Ph. 29 & 30) and joined a much larger lead farther downstream. Open water sections and leads were now more frequent in the sheet ice cover below the jam. The railway bridge was loaded with wagons full of heavy rock, a common practice to prevent movement of the superstructure in case of severe ice jams and runs. The Matapedia river was inspected again and little change was found since the previous day. It was mostly ice-covered except for a 9 km section, starting 4 km below Routhierville and extending upstream. This is well above the mouth. Shear walls were present in this reach, 1.2 m high and comprising ice blocks 10 cm - 30 cm thick.

1200-1800: No major changes in the Restigouche. The open section near Wyer's Brook was still 400 m long. At the toe of the downstream jam, ice blocks moved occasionally in the lead. Measurements on ice blocks stranded on the river bank indicated a thickness range of 40 - 75 cm, with an average value of 54 cm. The Upsalquitch R. was completely open with occasional ice jam remnants (Ph. 31).

1800-2100: The lead at the toe of the downstream jam extended 40 m into the rubble and the local water level had dropped by 0.20 m since the previous day. Further deterioration of the downstream sheet ice cover was evident by lengthening and joining of leads.

April 9

0800-0930: Pressure ridges were noticed near Flatlands, followed by moving ice blocks upstream to Bell Island and open water to Chessers Brook (2.6 km below the toe of the downstream jam). Shear walls had formed in the open section suggesting that a jam had formed and released. The lead at the toe of the downstream jam was wider and extended 70 m into the rubble (Ph. 32, 33). Local water levels had dropped by 0.6 m due to the ice movement farther downstream (Ph. 34). Upstream of the toe, however, the low road section remained submerged (Ph. 35). Water in the lead moved at considerable speed, 2 - 3 m/s and ice blocks were often released, a sign of imminent collapse of the jam. Close inpsection revealed the presence of small "pools" (diameter of several metres) in the rubble just upstream of the lead. Here, the water "boiled" intensely and water level differences between pools were visible, suggesting an extreme local slope (later estimated as 2% from the survey results). The ice bridges between the lead and the pools collapsed at 0930, resulting in farther upstream extension of the lead and considerable ice discharge. New pools then appeared farther upstream (see also Fig. 12).

0930-1200: At 0945, more ice moved into the lead and the ice discharge was maintained, bringing about the general release of the downstream jam (Ph. 36, 37). By repeated timing of ice floes, the surface velocity during 0950-1000 was determined as 3.2 m/s, a value that is in agreement with what is obtained using the simple theory of Henderson and Gerard (1981). With the passage of time, however, the

water speed decreased, as can be seen in the following observed values:

- average speed of ice front in first 20 min. of travel = 2.7 m/s
- average speed of ice front in next 25 min. of travel = 1.5 m/s
- local speed at former toe, 55 min. after release = 2.3 m/s

The ice run moved freely through the Matapedia confluence, splitting later into two, the North channel, along Quebec, and then through the channel between Long and Moses islands; and the South channel, along N.B., where if jammed just below Flatlands. By 1100, the ice run had thinned out to almost nil at the former toe site, indicating that the upstream jam did not move, as was confirmed later by observation. Large shear walls were left by the river banks as shown in Photos 38 - 41.

1200-1630: By 1400, the North channel run had been arrested by the intact ice cover between Gillis Island and the northern line of boom piers while the South channel run was slowing down near Christopher Brook just upstream of Tide Head (Fig. 2). The upstream jam by Wyer's Brook released at 1430 with an initial speed of 2.5 m/s. By 1620, the run reached the railway bridge, averaging 2.0 m/s. Ice conditions in the Matapedia R., during 1530-1630, were as follows. The lower 1 km was completely open. The next 2 km was covered with deteriorated sheet ice cover, followed by a 2 km long jam and open water to the St. Alexis road bridge, located some 9 km above the confluence. This was followed by 4 km of sheet ice, 5 km of open water, 8 km of sheet ice and open water. Evidence of previous jamming was present only in the latter reach of open water (Ph. 42).

1630-1900: The second ice run moved into the braided reach below Flatlands and joined the ice that had ran earlier in the day. Jamming in the N. channel caused some flooding of the islands. Near Flatlands, the jam was ~ 1.5 km long.

April 10

0900-1630: Little change occurred overnight. The shear walls were inspected and their height measured where possible (Fig. 13) so as to obtain approximate indications of the corresponding ice jam thickness (see also Calkins, 1983). Of particular interest is the rapid thickening of the jam near the toe, a feature predicted by theoretical analysis (see later discussion) and manifested in the planar geometry of the shear wall (photo 40).

1630-1900: A major ice run began in the Matapedia R. at 1630, entering the Restigouche at 1640 and arriving at the highway bridge by 1700. The surge associated with this run, travelling faster than the water and ice, dislodged the Flatlands jam before 1715. The ice again ran in the braided reach of the river with occasional brief jamming at various places. A jam that formed at 1820 in the tiny channel between Duffs Island and the South bank (Ph. 46), flooded a low lying property in Tide Head. By 1850, this jam extended 200 m above Christopher Brook. Riverside residences in this area are high enough to be usually safe but ice-flood damages can occur according to local residents (e.g. in 1975 when ice piled up on lawns some 11 m above the low tide level).

1900-2030: The Matapedia was completely open with abundant shear walls while most of the ice in the Restigouche was past Long Island.

April 11

No changes occurred overnight, other than consolidation of existing jams. Post-breakup conditions were observed from the air in the afternoon (Ph. 43). The Restigouche, Matapedia, Patapedia and Upsalquitch were completely open except for a small amount of ice rubble in the lower Restigouche, upstream of the sheet ice cover in the wide section starting at Atholville. Evidently, most of the rubble from upstream had been transported under the sheet ice. Shear walls were evident along the Restigouche and Matapedia (Ph. 43, 44) but not in the Patapadia. Ground inspection, revealed some road damage by flooding (ph. 45).

April 12

Most of the remaining ice rubble had disappeared and new leads had opened up in the sheet ice by Tide Head and Atholville. Observations were discontinued at 1100.

HYDROMETRIC DATA

Before analysing and interpreting our field observations, it is necessary to establish supplementary information such as ice thickness, discharge, channel bathymetry, and flow hydraulics.

Ice Thickness

As discussed earlier, winter measurements can be plotted versus degree-days of frost or days since freeze up and extrapolated to the end of winter, in the present case being March 23rd. This resulted in h = 64 cm. From this time on, melting should be occurring in accordance with Bilello's (1980) empirical equation:

$$\Delta h = \alpha S_T \qquad (3)$$

in which Δh = ice thickness reduction in cm; S_T = accumulated degree-days of thaw from a datum of -5°C for mean air temperature; and a = empirical coefficient in the range 0.4-1.0 cm/°C-day as determined by Bilello (1980) for 13 river sites in Northern Canada and Alaska. An approximate determination of a for the present case can be made by considering our measurements of h on stranded ice blocks after breakup. This gave a = 0.1 cm/°C-day.

Discharge

Under ice conditions, the flow rating curve for a gauging station does not apply because of the ice effect on stage which is particularly unpredictable during the breakup period. During the winter when flow and ice conditions are relatively stable, Water Survey of Canada (WSC) carries out discharge measurements at 4 to 6 week intervals. This information, together with stage records and

weather data, provides a basis for reliable flow estimates via interpolation. Once breakup starts, measurement of flow is generally out of the question and any estimates made are crude. In the present case, the problem is compounded by a concurrent malfunction of the gauge, starting sometime on April 4 and persisting until after ice clearance (April 18). An attempt to synthesize the flow hydrograph during breakup using our field data is presented next.

Considering that near the time of breakup most or all of the frazil slush has disappeared from under the sheet ice cover, an approximate rating curve could be generated using plausible ice and bed roughness values. For the ice, it was assumed that $n = 0.020$ while the open-water relationship between n and hydraulic radius for the bed was utilized for the bed-controlled flow layer (see also Beltaos, 1983). This approach results in Eq. 2, presented earlier. Using Eq. 2 with $h'=0.60$ m and the recorded stages up to April 4, the discharge can be calculated and plotted versus time, as shown in Fig. 14. Extrapolation of gauge levels to April 5 and 6, taking into account prevailing temperature and rainfall, resulted in the data points designated by the inverted triangles. (For April 5 and 6, estimates were also obtained by running the model RIVJAM, as will be discussed later). It is noteworthy that the synthesized hydrograph is consistent with the rainfall pattern and with the observed steadiness of ice and water conditions during April 6-8.

An additional check on the discharge can be made by consideration of the hydraulics of flow under ice jams. From the measured water levels, river cross-sections, and shear wall heights, approximate flow areas and water surface slopes can be calculated near the toe of the

April 6 jam. With this information, one can then examine the relationship (Beltaos and Wong, 1986):

$$Q_T = Q_f + \lambda A_J \sqrt{S_w} \qquad (4)$$

in which Q_T = total discharge; Q_f = discharge under the jam (it can be estimated using plausible roughness coefficients); S_w = water surface slope; A = wetted cross-sectional area of the jam; and λ = seepage coefficient (m/s), so that $\lambda A_J \sqrt{S_w}$ represents the discharge through the voids of the jam. Assuming that Q_T and λ are constant along the jams, Eq. 4 suggests that a plot of $A_J \sqrt{S_w}$ versus Q_f should be linear with a slope of $-1/\lambda$ and an intercept of Q_T. This is tested in Fig. 15 where the data points for five sections near the toe are well described by a straight line. The intercept gives Q_T = 290 m^3/s and the slope gives λ = 2.3 m/s. Both these values are close to what has been deduced from mathematical modelling of the jam configuration, as will be discussed later.

Hydraulic Data

Immediately after the breakup, the field notes, photos, and measurements were processed and reviewed so as to define the types of analysis to be pursued. Consequently, requirements emerged for supplementary field work, carried out in July of 1988, and comprising cross-sectional bathymetry at numerous sites, prevailing water levels and slopes, etc. (e.g. see Figs. 16 and 17).

DATA ANALYSIS AND INTERPRETATION

There are two major questions regarding breakup. First, how to anticipate and forecast whether and when it will start in response to an approaching runoff event; and second, how to predict the water levels and damage potential of the various ice jams that are likely to form.

Initiation of Breakup

This event is defined as the first sustained movement of the intact ice cover at a given site. Once in motion, an ice sheet will quickly break down into small blocks by impacting on other ice sheets or on channel boundaries which eventually leads to jamming. No universally applicable criteria exist as yet for the initiation of breakup. River stage is known by experience to be a usefull index provided it is expressed in terms of antecedent conditions (e.g. freeze up stage, ice thickness, degree-days of thaw, etc). Beltaos (1990) describes the physical background for such empirical findings and gives several examples of quantitative criteria along with associated coefficients. For the Restigouche R. at RGB, analysis of past gauge records led to the approximate criterion illustrated in Fig. 18. Here, $(S_T)_B$ is the accumulated degree-days of thaw up to the time of initiation using a base air temperature of -5°C (= 90°C - days for 1988). The parameter h_{io} is the end-of-winter sheet ice

thickness (= 64 cm for 1988) while H_F is the preceeding freeze up stage (= 2.0 m for 1988) and H_B is the stage at which breakup is initiated. Because of the gauge malfunction, all we know about H_B is that it is more than 2.3 m. Thus, the quantity χ_B in Fig. 18 is less than 1.3 m for 1988 and is plotted accordingly. Though only partly known, the plotting position of the 1988 event is not inconsistent with previous findings, obtained from past hydrometric station records (1969-87).

To apply the criterion of Fig. 18 as a forecasting tool, one needs to predict water stages as well as air temperature. The former requires development of a runoff model so as to relate weather forecasts to discharge which, in turn, can be translated into stage. The latter can then be compared to the current value of H_B, obtained from Fig. 18 using updated values of $(S_T)_B$.

Ice Jam Profiles

The jam that formed on April 5 remained in place for 3.5 days which enabled us to get detailed data. First, it is noted that little change in local water levels occurred during April 6-8 which implies a steady-state condition. Second, the available data suggest that the jam was practically grounded at the toe (Fig. 19). Such conditions are often mentioned by observers on the basis of visual inspection but not previously documented by measurement. The configuration of ice

jams near their toe relates to how they are held in place and thus to their stability, persistence, and possible dislodgement techniques.

The present field data afford an opportunity to apply the model RIVJAM, developed recently at NWRI, and designed especially to compute toe conditions and grounding, a capability not available in other ice jam models. RIVJAM is a one-dimensional, steady-state model that solves two simultaneous differential equations to compute the water surface elevation and the thickness of a jam as functions of river distance (Beltaos and Wong, 1990). It "marches" either upstream or downstream starting from a site where the jam thickness and water level are specified. In the present case we can proceed upstream, starting at the toe (Sec. 20.635 km) and using the locally measured water level and jam thickness deduced from the shear walls. Evaluation of model output was made on the basis of three criteria deriving from observations (Fig. 20):

1. How well the model reproduces the observed water levels and thicknesses in the reach 20.6 km - 21.3 km where accurate water levels are available;
2. How well the model reproduces jam thicknesses upstream of 21.3 km where water levels are not available; and
3. Whether the model predicts an "equilibrium" condition (approximately constant thickness and flow depth) starting a short distance from the toe, as should have been the case given that the jam was 18 km long on April 6.

Several coefficients and parameters have to be specified in order to run RIVJAM, including λ and Q_T. As explained by Beltaos and Burrell (1990a), these coefficients were chosen from previously established ranges but λ and Q_T were varied until the above mentioned

criteria were satisfied. Good results were obtained with Q_T = 330 m^3/s and λ = 2.5 m/s. These values are in agreement with those estimated earlier by different considerations (290 and 2.3, respectively; see also Fig. 15). Moreover, the model helps establish the maximum breakup level at the RGB gauge, otherwise unknown due to malfunction, as 20.62 m. This represents a gauge height of 6.58 m which suggests that 1988 represents the fourth most severe breakup since 1969. The calculated water level at RGB is consistent with the fact that ice blocks were left stranded on the bank in the vicinity of the gauge house.

It is also of interest to apply RIVJAM to the Apr. 5 jam which was not fully developed and ended near the gauge. The associated water level data are not accurate as they were obtained from photos, and there are no data on ice jam thickness. However, Fig. 21 indicates that RIVJAM predicts the location of the jam head closely if Q_T is set at 315 m^3/s. It is also noted that other model coefficients were selected from plausible ranges (see Beltaos and Burrell, 1990a, for details). The only exception is the value of λ, for which no previous field determinations exist (see also later discussion). In this application, too, the calculated water level at the RGB gauge is consistent with a visual estimate placing it ~ 1 m below the top of the bank, in the evening of April 5.

DISCUSSION

The 1988 breakup event was of the mechanical type, accompanied by considerable jamming and some flooding of low lying areas. Rainfall was a major factor in determining both the onset and the severity of the breakup. In the study reach, the breakup of the Restigouche ice cover was triggered by the opening up of the Upsalquitch, as is often the case. This led to a relatively short jam and water levels that threatened but did not cause any flooding. However, the subsequent release of a large quantity of broken ice in the reaches upstream of the Upsalquitch confluence, produced a much longer jam and considerably higher water levels.

While some deterioration of the ice cover occurred prior to and during the breakup ($(S_T)_B$ = 90°C-days above -5°C), enough thickness and strength remained to restrain the April 5 jam for three and a half days. The release of the jam was clearly related to the gradual enlargement of the open lead at the toe that began forming in the morning of April 6. Such leads are observed commonly in large river jams and always appear to be intimately related to the release of the jam. It is not known at present why they form and expand as they do. More observations are needed in rivers like the Restigouche where, thanks to excellent accessibility, quantitative data can be obtained and interpreted using mathematical models of ice jams. This type of approach should lead to an understanding of toe conditions and release mechanisms. Our measurements suggested considerable grounding at the toe of the jam, a condition that has often been suspected on the basis of visual evidence but not previously documented by measurement.

Applications of the RIVJAM model to the ice jam profiles of April 5 and April 6-8 were encouraging in that good agreement with measurements was obtained while model parameters were selected from plausible ranges. One possible exception is the seepage parameter, λ, being considerably higher than what would have been expected by extrapolation of laboratory test results (Beltaos and Wong, 1986). Clearly, more case studies of grounded jams are needed.

While the present data represent a first and relatively reliable set on the configuration of ice jam toe areas, several shortcomings can be identified. For example, water level surveys are time-consuming so that successful completion depends on the jam remaining stable for, at least, several hours. It is still not possible to measure the thickness of an ice jam, a very important factor in modelling and flooding potential. The shear wall heights that are measured after release only provide indirect and crude estimates that merely apply to the latest thickness attained prior to the release. Moreover, the measurement of shear wall heights can be tedious and even unsafe unless some precautions are taken, e.g. safety harness.

SUMMARY AND CONCLUSIONS

The Restigouche River Ice Project was initiated in 1987 in order to study the characteristics of breakup and associated ice jams, known to have caused serious flooding in the past. The results of the first year's observations and measurements are reported herein, following a brief discussion of background material obtained from existing hydrometric records.

The 1988 breakup was triggered by that of the Upsalquitch River and proved to be of moderate severity, causing limited flooding of the lowest sections of the riverside roads in both New Brunswick and Quebec. This occurred when a large amount of broken ice from the Restigouche above the Upsalquitch mouth joined a short jam that had formed on April 5 near Babcock Brook, a few kilometres downstream of the Upsalquitch. The conditions of breakup initiation in 1988 were consistent with previously formulated criteria based on the records for the hydrometric station near Rafting Ground Brook.

Measurements of the jam levels and shear wall heights after the jam released on April 9, indicated severe grounding at the toe of the jam. Mathematical predictions of the jam's configuration using the model RIVJAM were successful with plausible choices of the various model coefficients. The exception was the seepage parameter, λ, for which no previous field data exist. More case studies are needed to elucidate this and to further test the RIVJAM model. It is noteworthy that this is the first time that quantification of ice jam toe conditions and grounding has been possible, largely thanks to the geomorphic characteristics of the Restigouche River and the accessibility of the study reach.

Two areas that will require continued attention and analysis were identified. First, the mechanics of flow through ice jams is only beginning to be investigated, particularly as it relates to conditions of grounding. And, second, the formation and evolution of open leads at ice jam toes need considerable study in order to explain the relationship of such leads with the eventual release of jams.

ACKNOWLEDGMENTS

The authors thank the technical and support staff of NWRI and NBDOE for their contributions to the project. Special thanks are due to W.J. Moody, Senior Technologist at NWRI, who directed the hydraulic surveys following breakup; D. Comeau and W. Waite of NBDOE who provided specialized weather forecasts and climatological information; and L. Irvine, local resident, who carried out ice reconnaissance and provided advice as to the imminence of the breakup event.

REFERENCES

Beltaos, S. 1983. River ice jams: theory, case studies and applications. ASCE J. of Hydr. Engrg., Vol. 109, No. 10, pp. 1338-1359.

Beltaos, S. 1984. Study of river ice breakup using hydrometric station records. Proc., Workshop on Hydraulics of River Ice. Fredericton, N.B., Canada, pp. 41-59.

Beltaos, S. 1987. Ice freeze up and breakup in the lower Thames river: 1983-84 observations. National Water Research Institute Contribution 87-19. Burlington, Ont., Canada.

Beltaos, S. 1990. Fracture and Breakup of river ice cover. Can. J. of Civ. Engrg., Vol. 17, No. 2, pp. 173-183.

Beltaos, S. and Burrell, B.C. 1990a. Case study of a grounded jam; Restigouche R., N.B. National Water Research Institute Contribution 90-67, Burlington, Ont., Canada (submitted to Northern Hydrology Symposium, Saskatoon, July 1990).

Beltaos, S. and Burrell, B.C. 1990b. Restigouche River Ice Project. Submitted to Eastern Snow Conference, Bangor, Maine, June 7 & 8, 1990.

Beltaos, S. and Wong, J. 1986. Preliminary studies of grounded ice jams. Proc., IAHR Ice Symposium, Iowa City, Iowa, U.S.A., Vol. 2, pp. 3 - 14.

Beltaos, S. and Wong, J. 1990. Ice jam configuration: second generation model. National Water Research Institute Contribution 90-65. Burlington, Ont., Canada (submitted to ASCE Cold regions Engineering Conference, Feb. 1991, Hanover, N.H., USA).

Bilello, M.A. 1980. Maximum thickness and subsequent decay of lake, river and fast sea ice in Canada and Alaska. U.S. Army Corps of Engineers, CRREL Report 80-6, Hanover, N.H., U.S.A.

Calkins, D.J. 1983. Ice jams in shallow rivers with flood plain flow. Can. J. of Civ. Eng. Vol. 10, No. 3, pp. 538-548.

Gidas, N.K. 1979. Analyse des diverses solutions possibles au problème d'inondation de Matapedia. Etude No. 0116-2, Direction General des Eaux, Ministère des Richesses Naturelles, Quebec, P.Q., Canada.

Gidas, N.K. 1981. Recherche sur les meilleures contre les inondations de la Matapedia causées par les embacles. Proc., International Symposium on Ice, Vol. 1, IAHR, Quebec, P.Q., Canada, pp. 266-275.

Henderson F.M., and Gerard, R. 1981. Flood waves caused by ice jam formation and failure. Proc., International Symposium on Ice, Vol. 1, IAHR, Quebec, P.Q., Canada, pp. 277-287.

Leger, R.D. 1986. A report on ice jams on the Restigouche river basin. New Brunswick Department of the Environment, report prepared under the employment action program. Fredericton, N.B., Canada.

Prowse, T.D., Beltaos, S., Burrell, B.C., Tang, P., and Dublin, J. 1989. Ice breakup of the Nashwaak river, New Brunswick. Proc., Eastern Snow Conference. Quebec, P.Q., Canada, pp. 142-155.

Tang, P., Burrell, B., Lane, R., and Beltaos, S. 1986. Study of ice breakup in Meduxnekeag river, N.B., using hydrometric station records. Proc., Fourth Workshop on Hydraulics of River Ice. Montreal, P.Q., Canada.

Wong, J. and Beltaos, S. 1986. Ice freeze up and breakup in the upper Grand river: 1982-83 observations. National Water Research Institute Contribution 85-12. Burlington, Ont., Canada.

Table I. Open-Water, Reach-Average Hydraulics of Restigouche River Near the Gauge by Rafting Ground Brook.

Gauge Height (m)	Discharge (m^3/s)	Flow Depth (m)	Average Velocity (m/s)	(1) n_b ($\frac{1}{m^{\frac{1}{3}}}$ s)	(2) K_b (m)
0.70	33	1.0	0.29	0.100	3.12
1.00	84	1.2	0.56	0.058	1.32
1.50	240	1.5	1.10	0.035	0.30
2.00	460	1.9	1.56	0.028	0.12
2.50	740	2.2	1.98	0.025	0.06
3.00	1050	2.7	2.28	0.024	0.06
3.50	1380	3.1	2.53	0.024	0.06
4.00	1710	3.5	2.69	0.025	0.06

(1) Manning coefficient

(2) Calculated equivalent sand-roughness height of the bed.

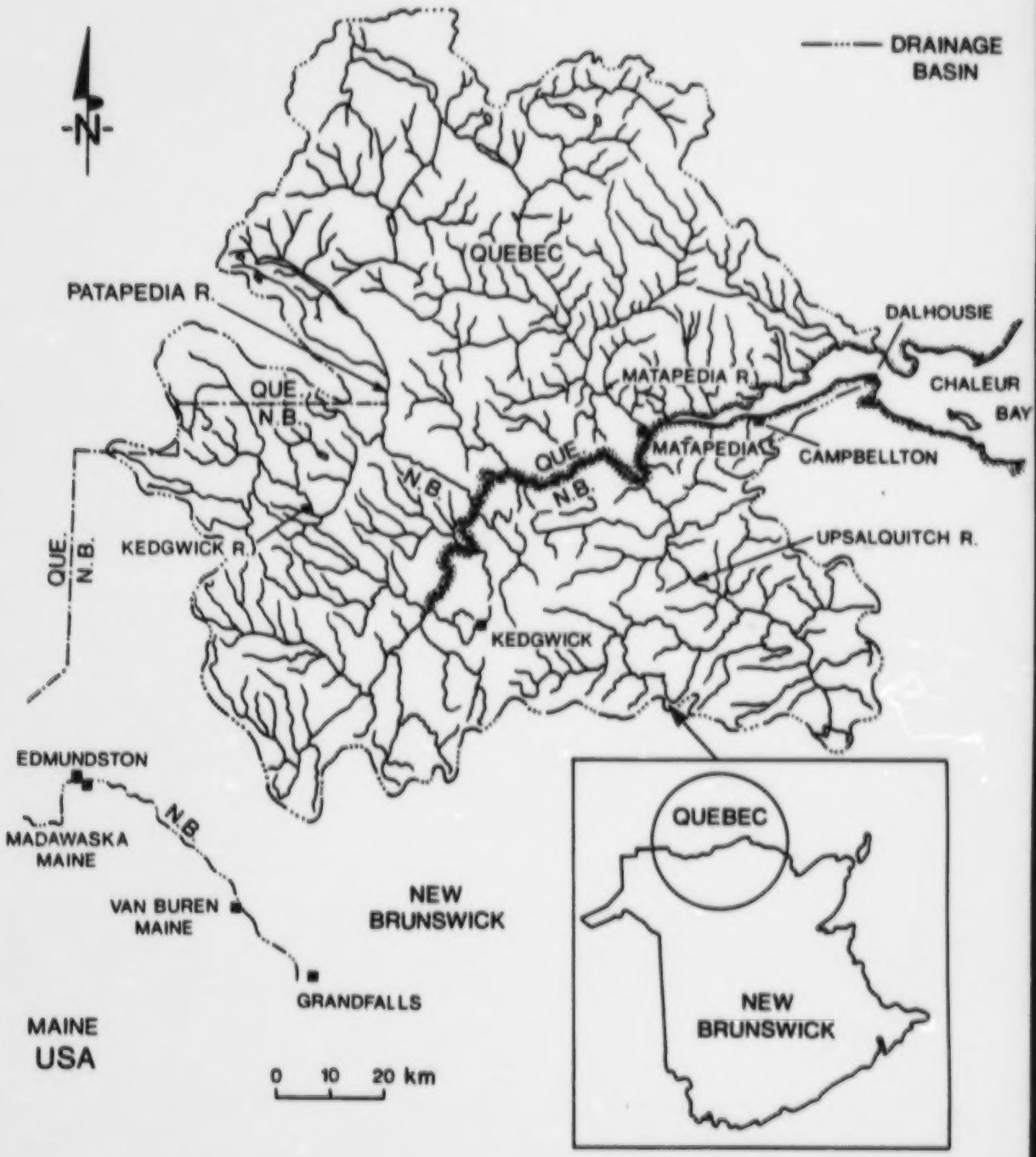


Fig. 1 Restigouche River Basin

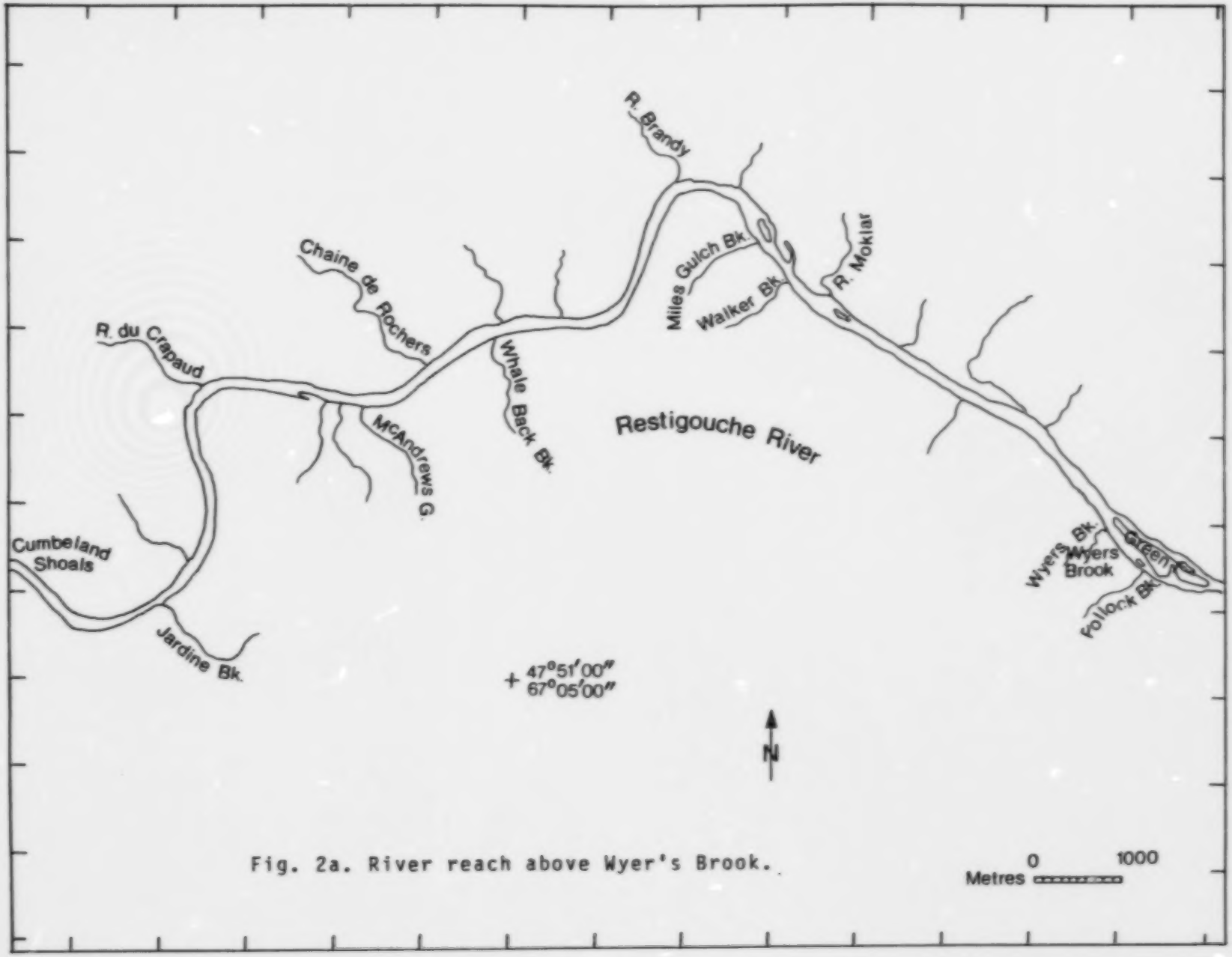


Fig. 2a. River reach above Wyer's Brook.

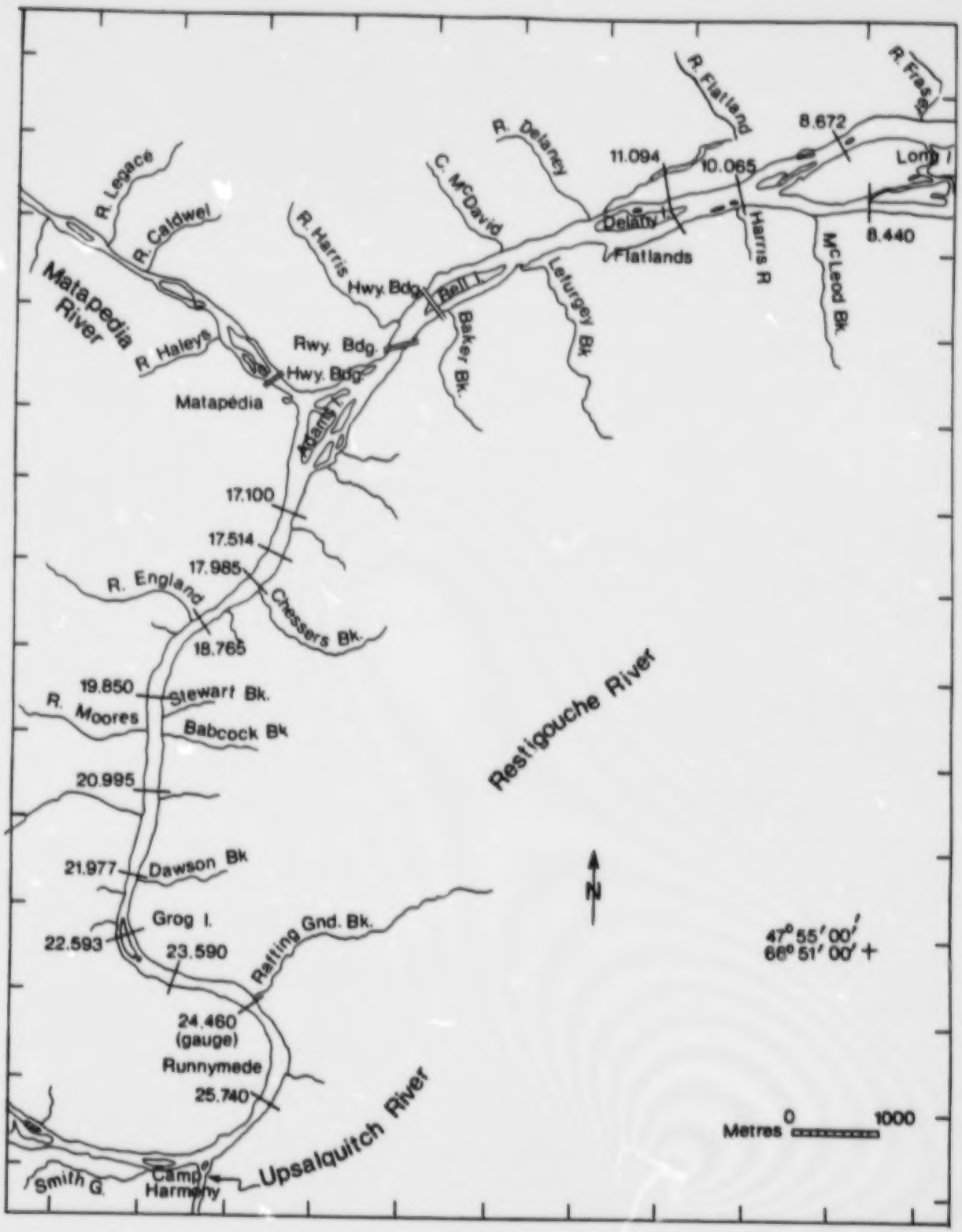


Fig. 2b. Study Reach (Cross-sections are labelled by their distances from Old Mission Point in kilometres)

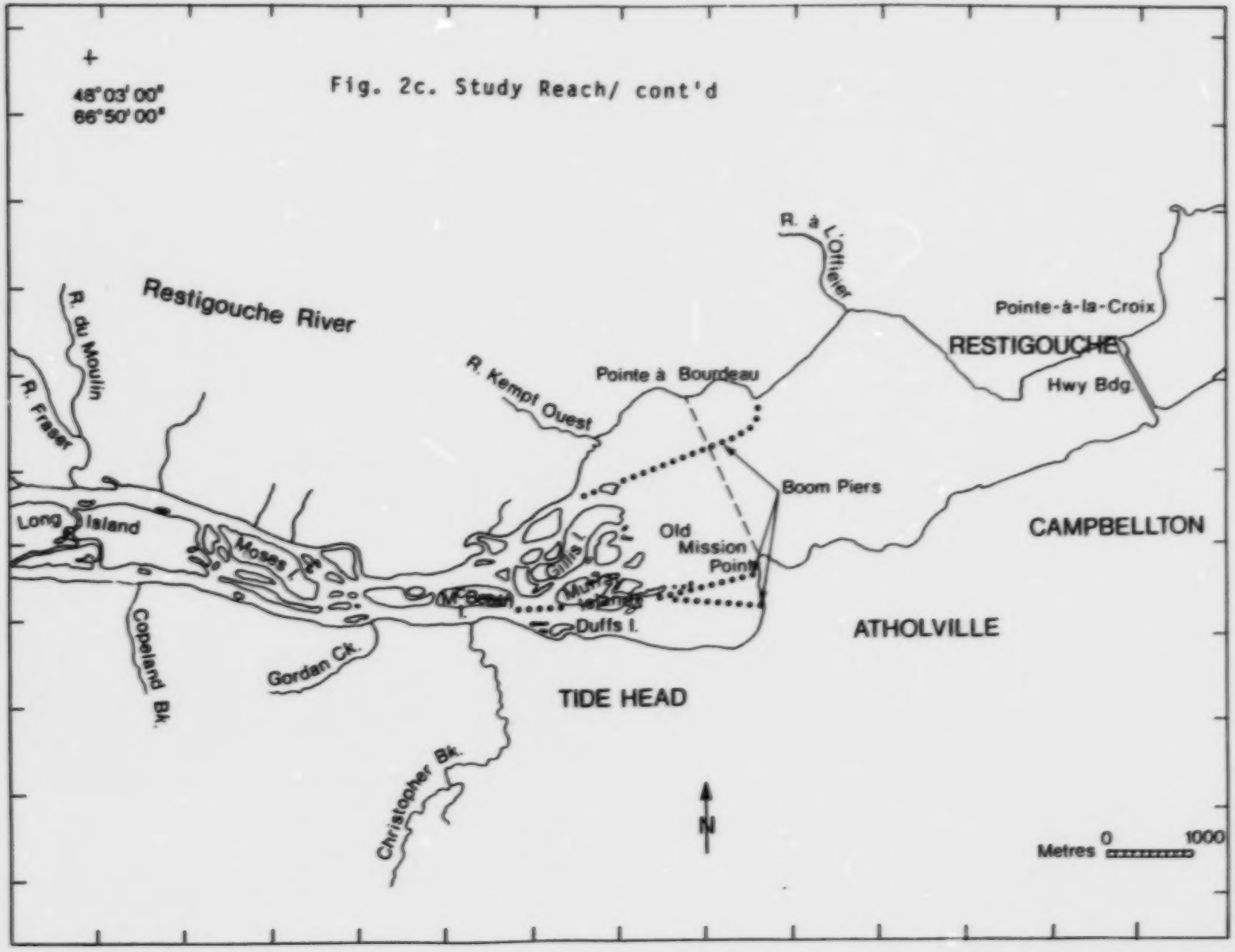


Fig. 2c. Study Reach/ cont'd

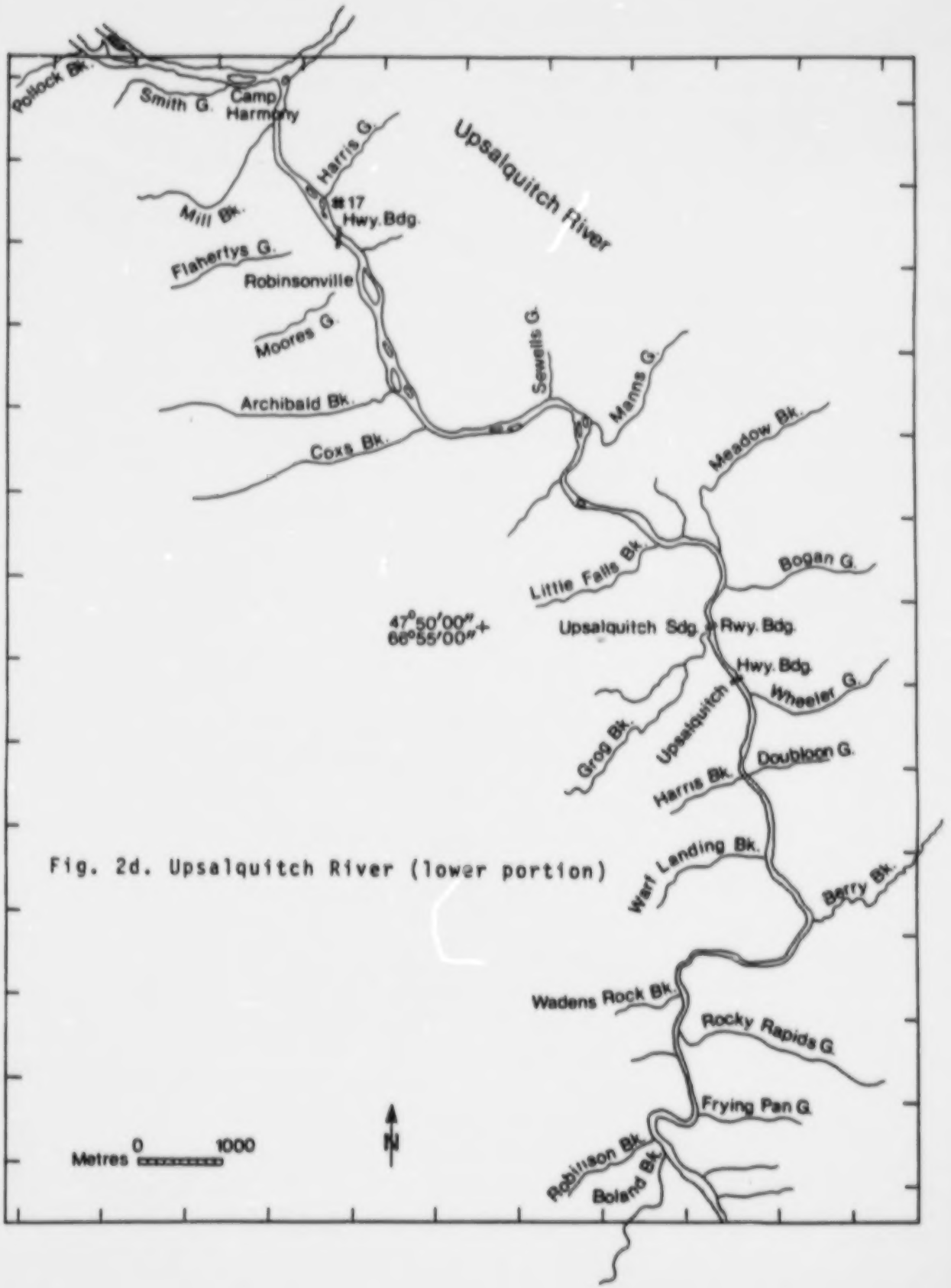


Fig. 2d. Upsalquitch River (lower portion)

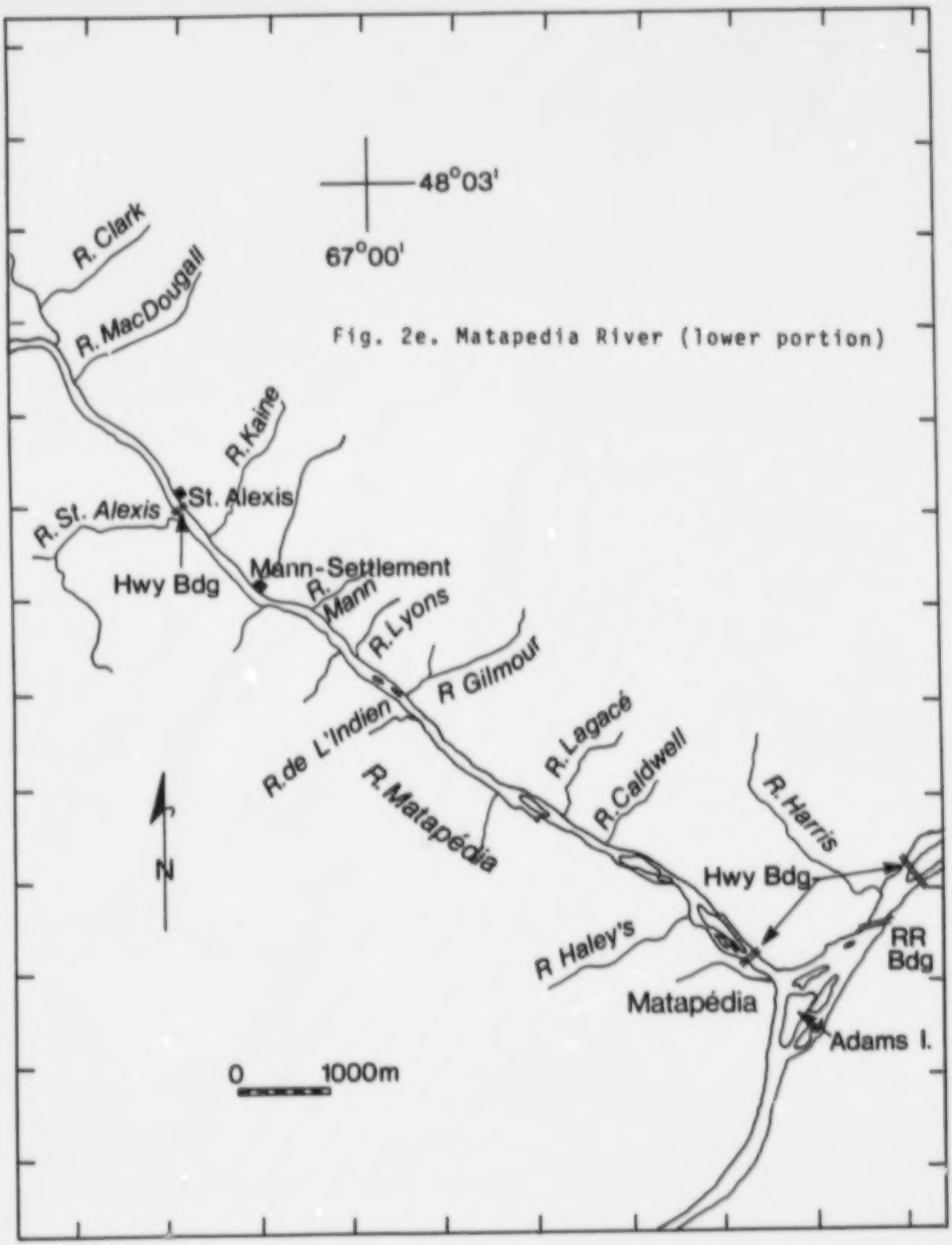


Fig. 2e. Matapedia River (lower portion)

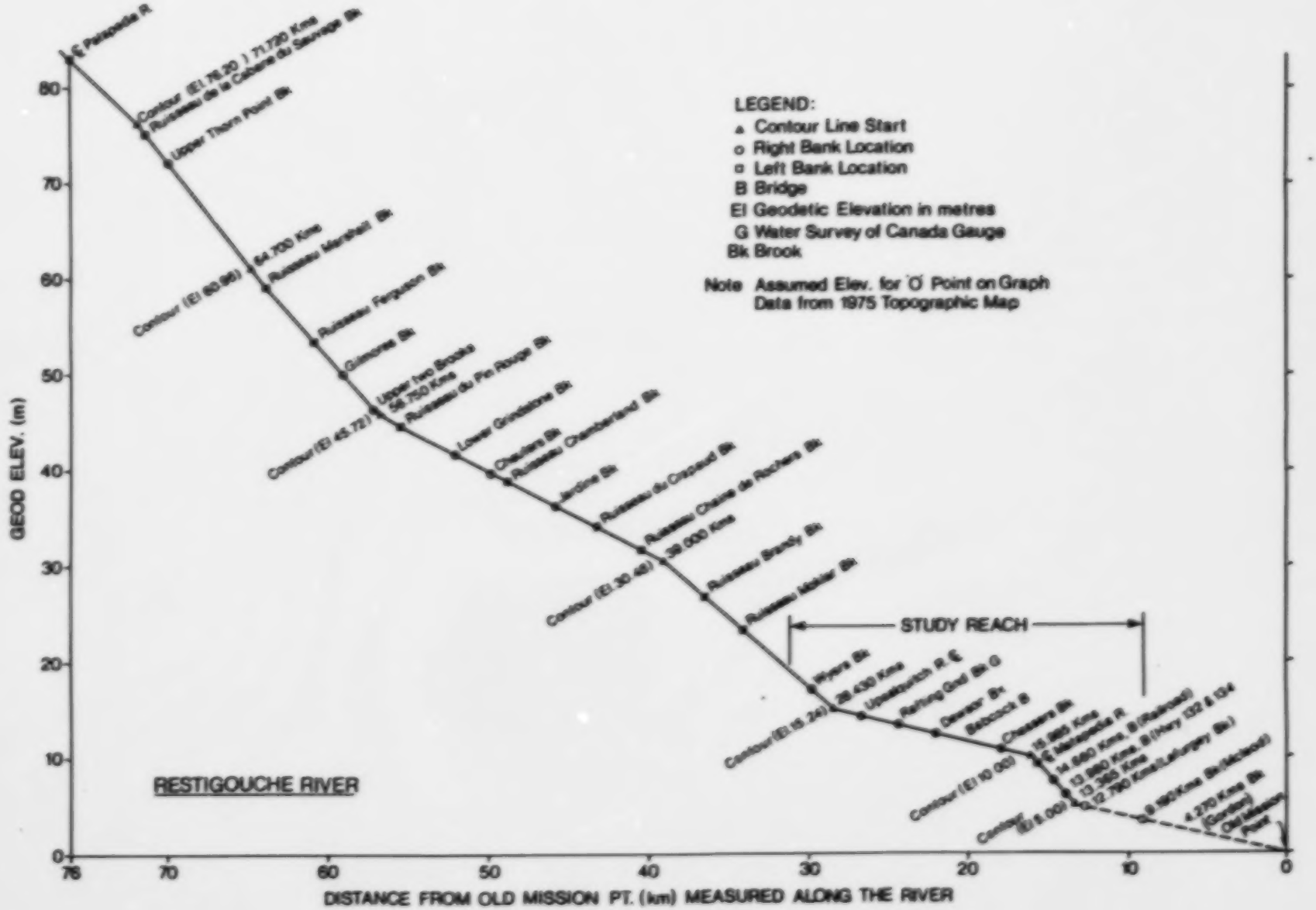


Fig. 3. Longitudinal Profile of Restigouche River, based on existing topographic maps. Elevations are indicated in metres.

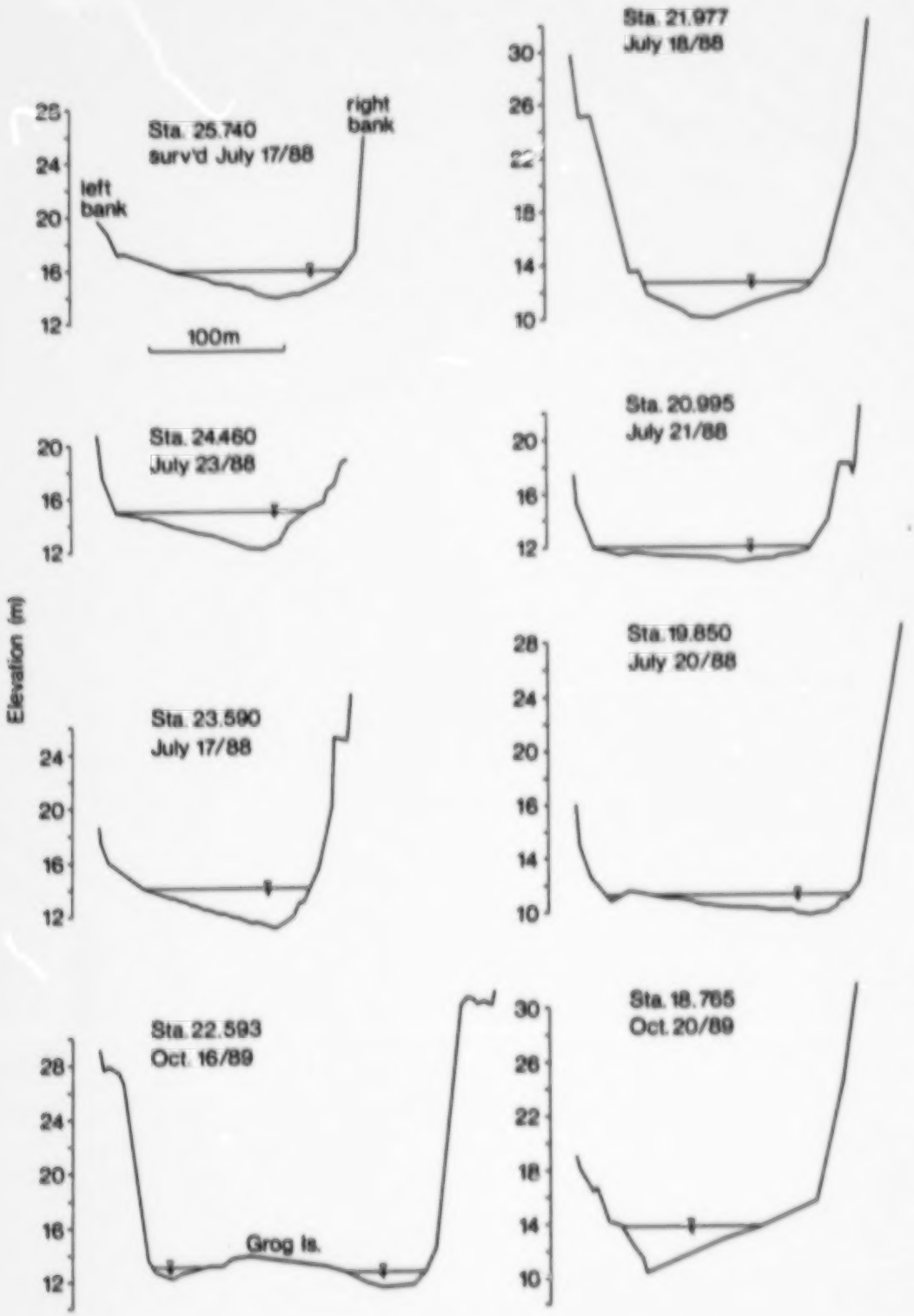


Fig. 4. Selected Cross-Sections of the Restigouche River in the Study reach. "Left" and "right" refer to an observer facing downstream.

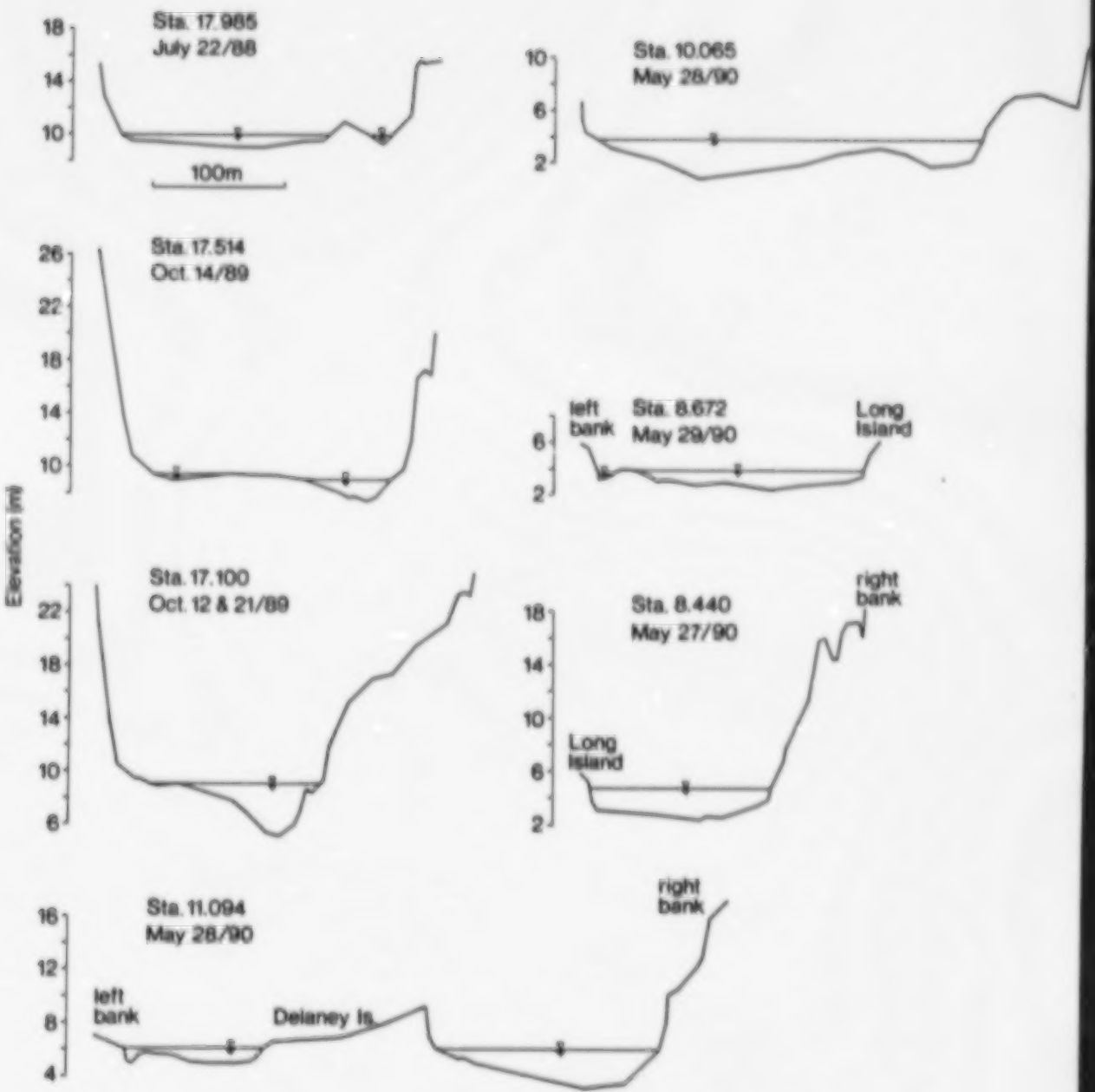


Fig. 4. Concluded

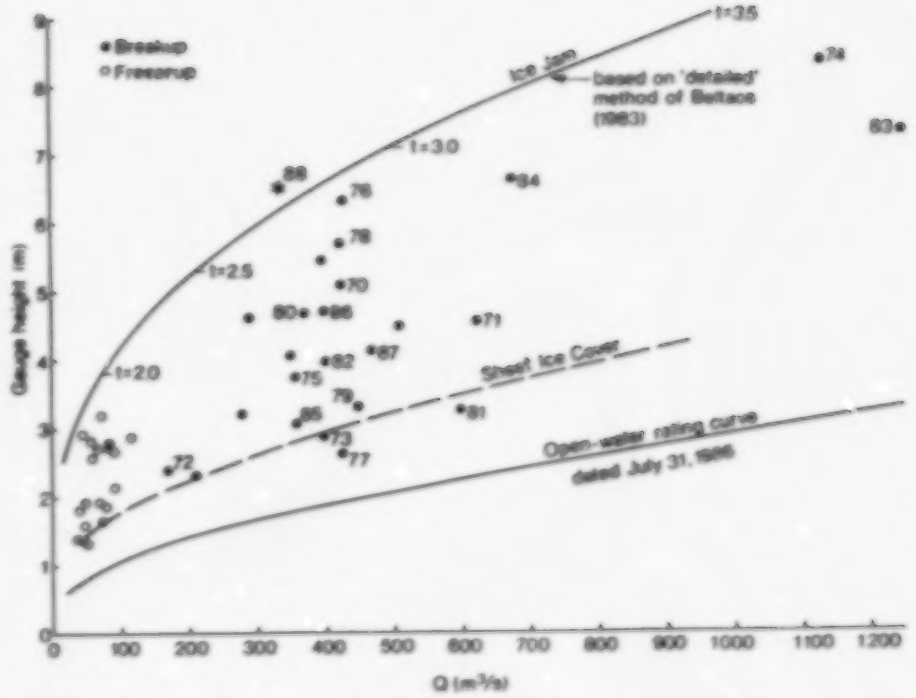


Fig. 5. Maximum breakup water levels at Rafting Ground Brook, plotted versus discharge. Data points are based on analysis of gauge records (1969-87) and on authors' measurements and calculations (1988). Freeze-up levels are also shown for comparison. "Thermal" events, where there is no ice run and the ice cover largely disintegrates in place plot near the "Sheet Ice Cover" curve, synthesized from measured river cross-sections and hydraulic resistance calculations.

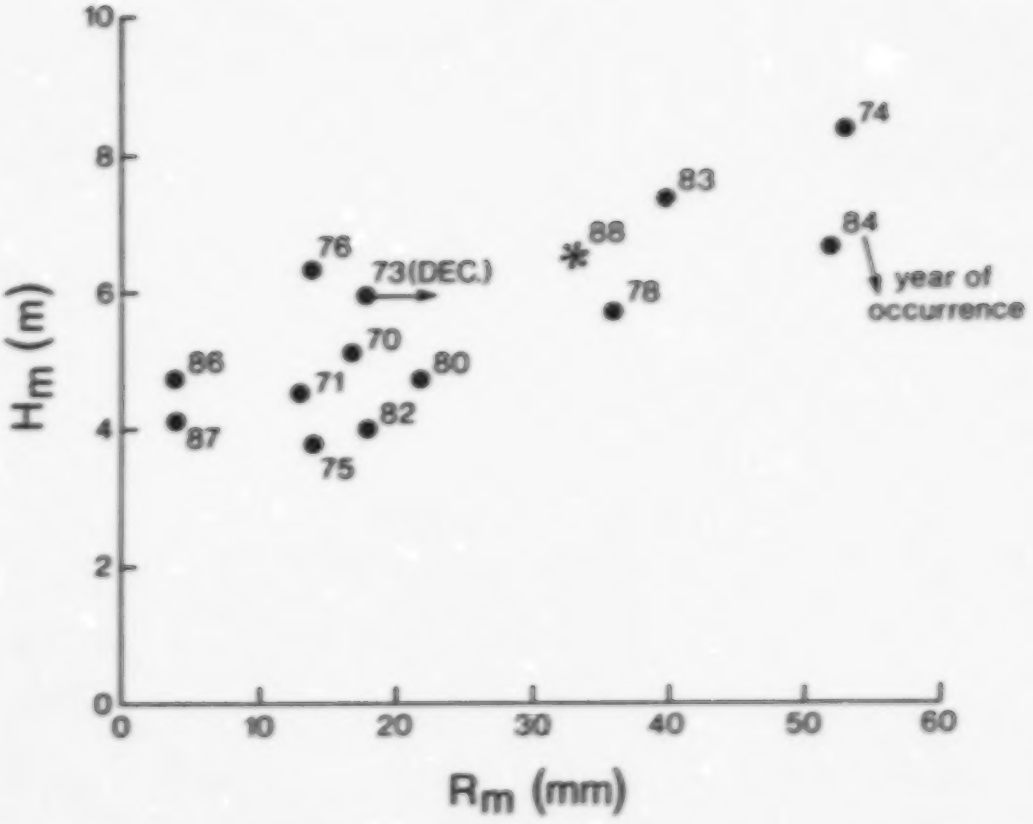


Fig. 6. Effect of rainfall on maximum breakup water level at Rafting Ground Brook. H_m = maximum gauge height registered during the breakup period; R_m = accumulated rainfall from the "end of winter" to the time of H_m. Thermal breakup events are omitted.

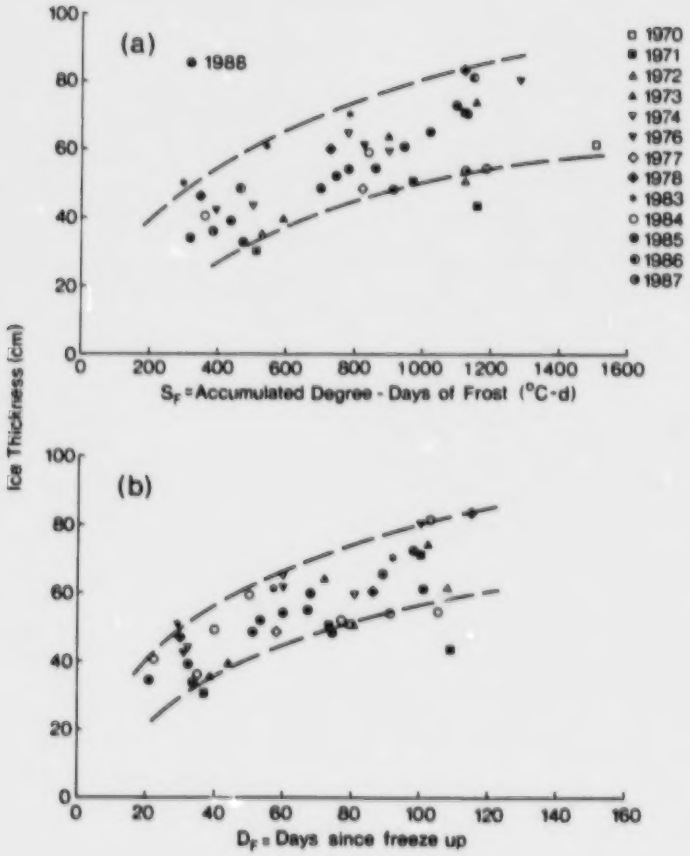


Fig. 7. Growth of thermal ice cover during the winter
(a) thickness versus degree-days of frost since freeze up;
(b) thickness versus days since freeze up.

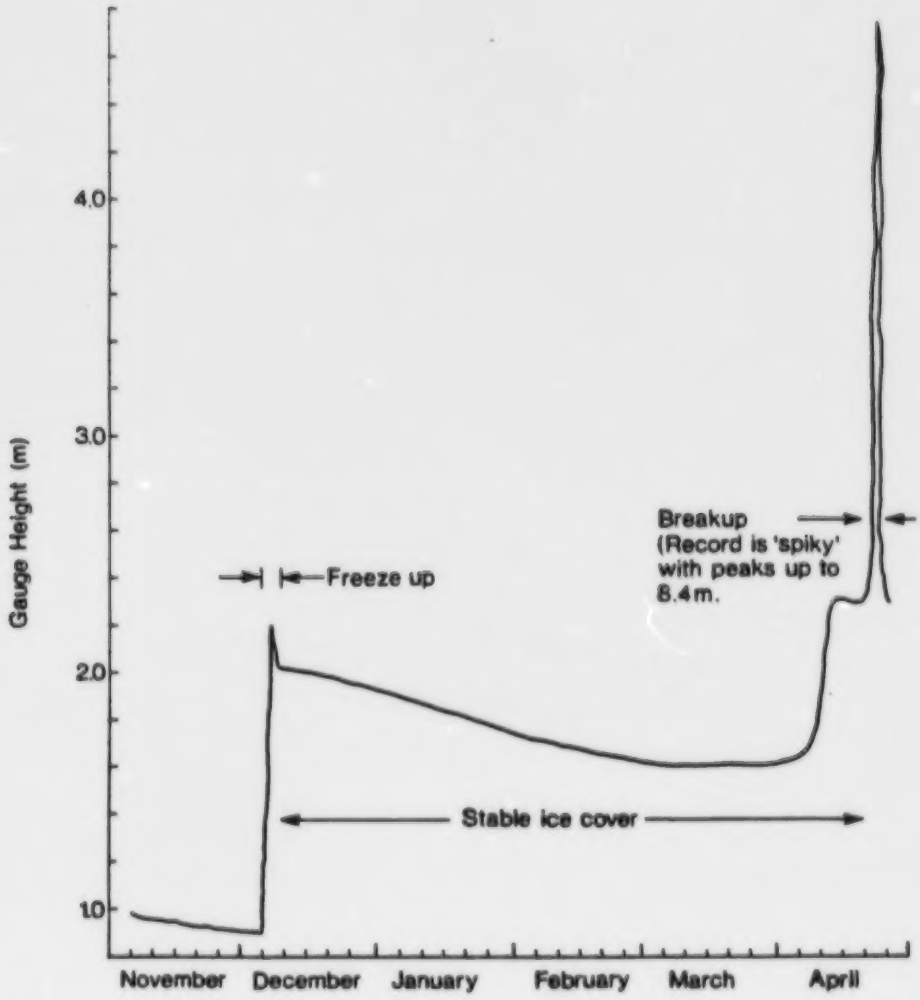


Fig. 8. Typical variation of river water level in winter. Geodetic elevation = gauge height plus 14.04 m.

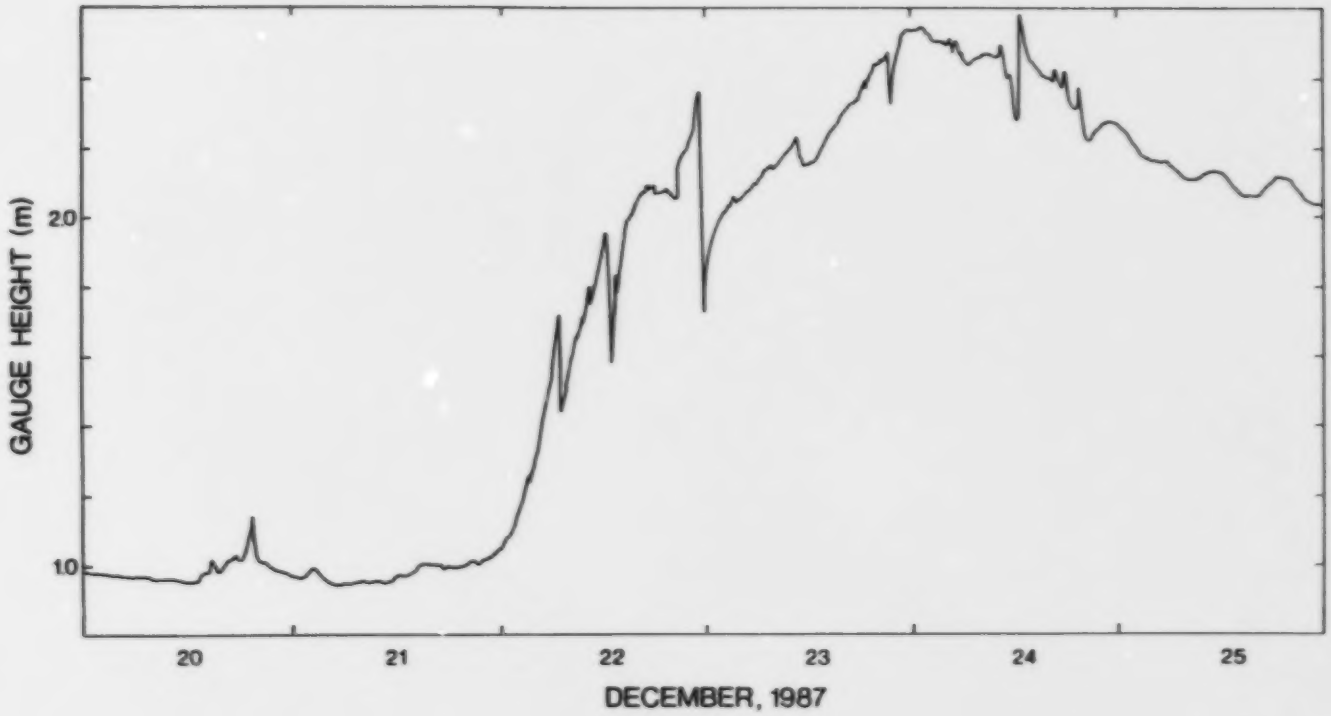


Fig. 9. Variation of water level at freeze up. Reproduced from Water Survey of Canada records.

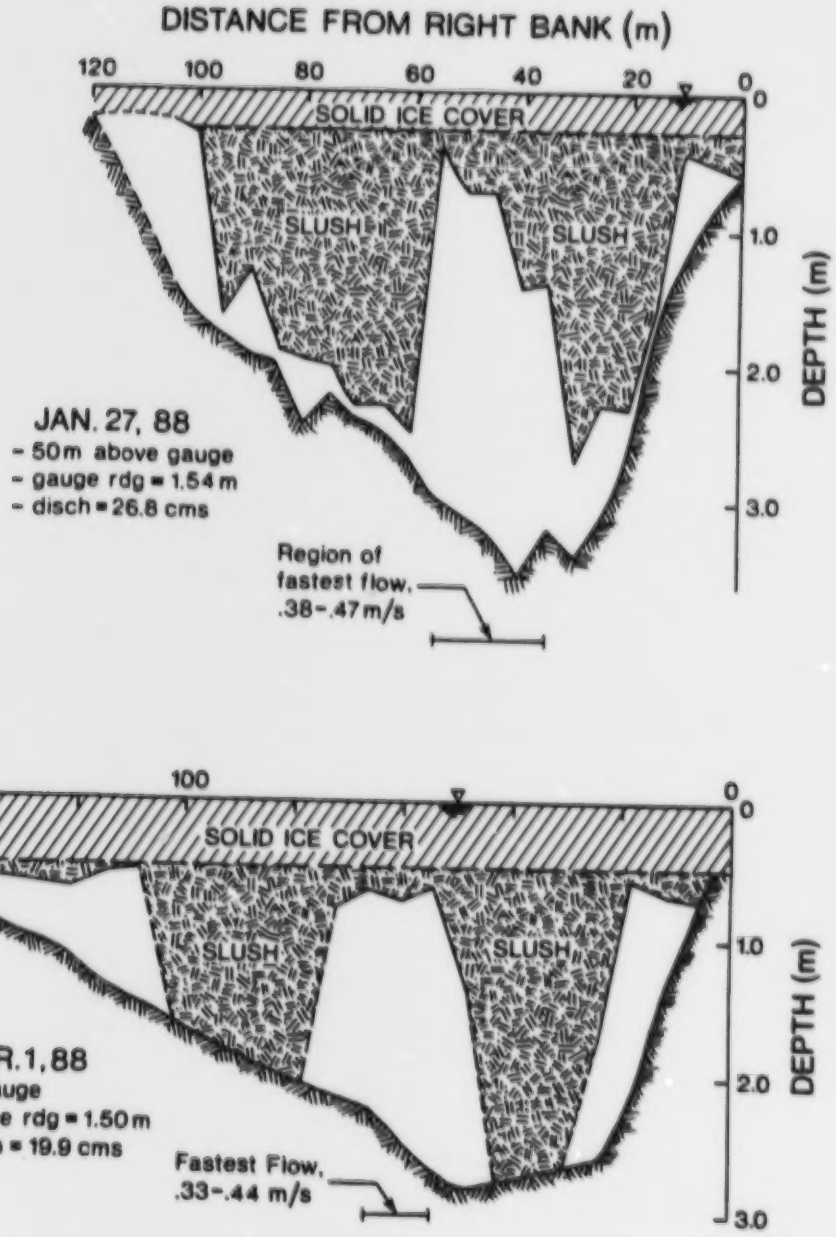


Fig. 10. River ice conditions during the winter at cross-sections near the Rafting Ground Brook Gauge. Based on data provided by Water Survey of Canada.

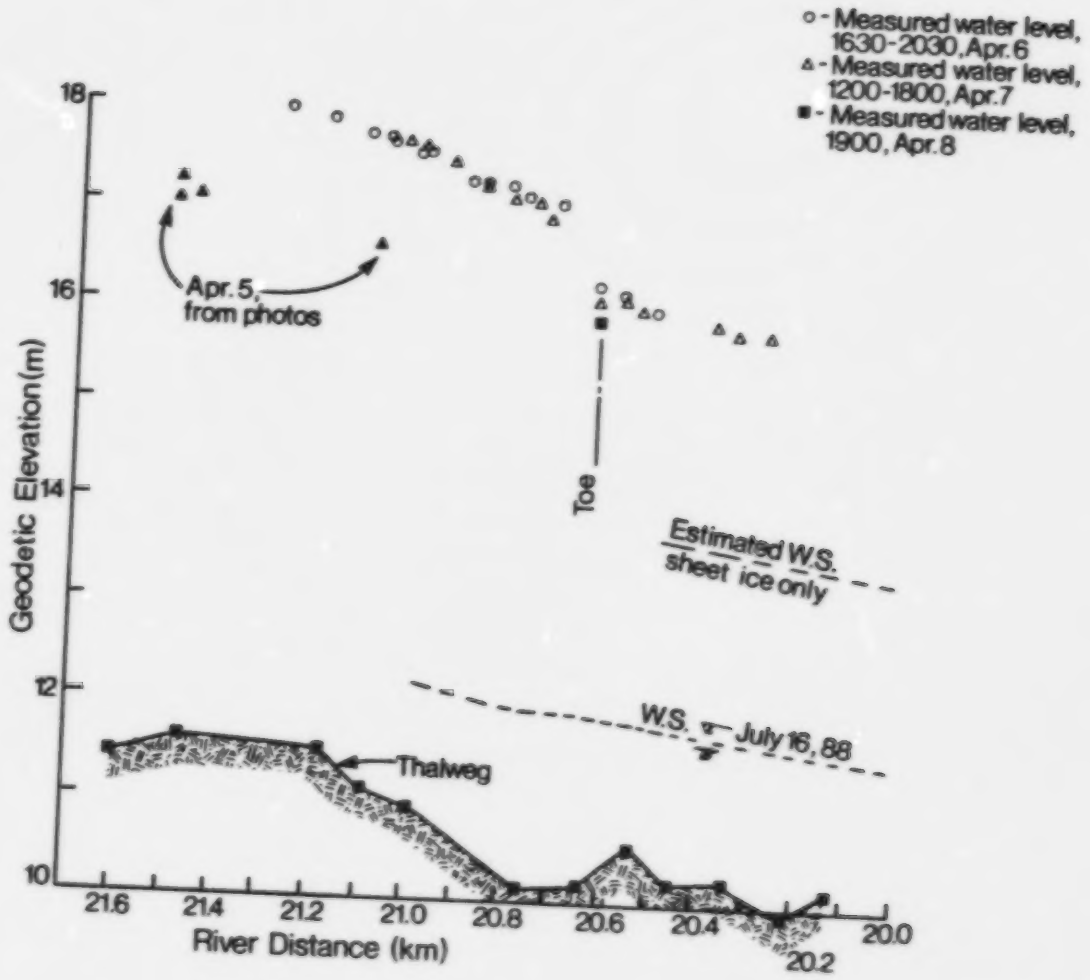
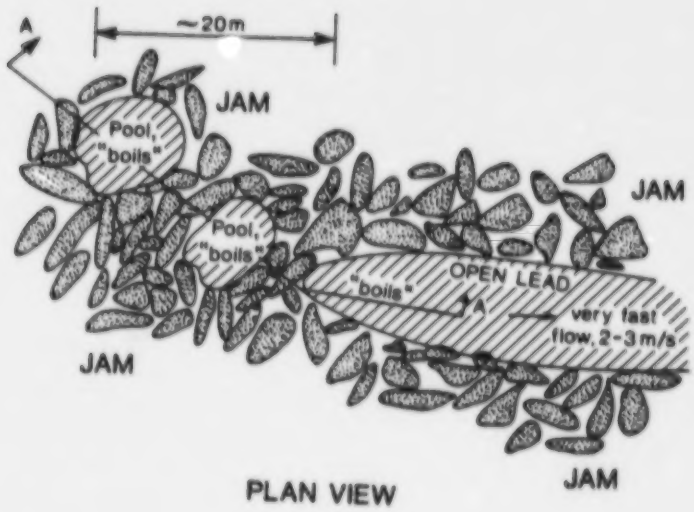
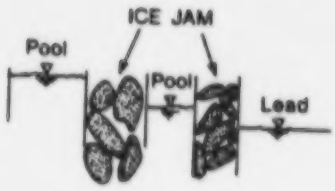


Fig. 11. Measured water levels near toe of jam. River distance is measured upstream from Old Mission Point, Atholville.



PLAN VIEW



SECTION A-A

Fig. 12. Observed conditions near the toe of the jam, shortly before its release at 0945, April 9.

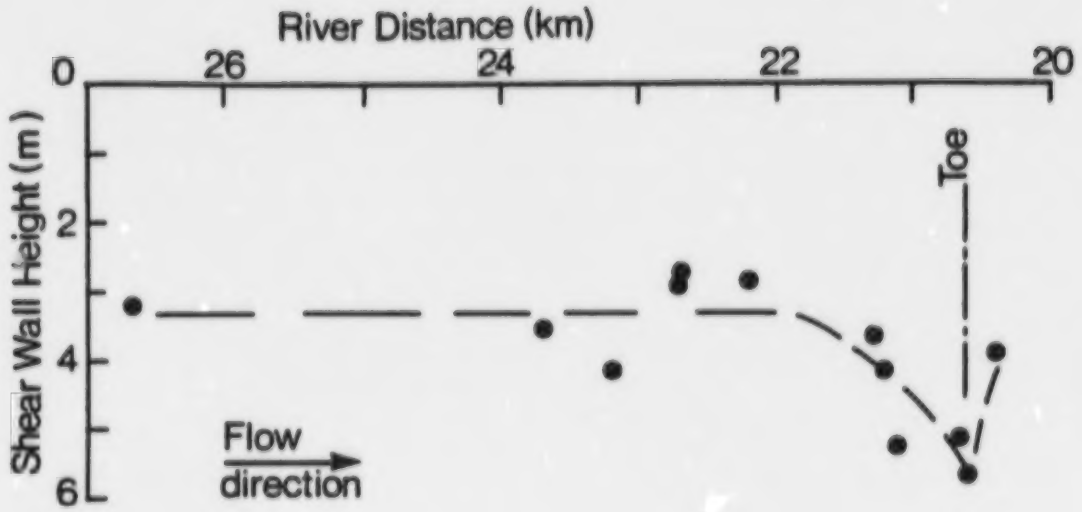


Fig. 13. Longitudinal variation of shear wall height.

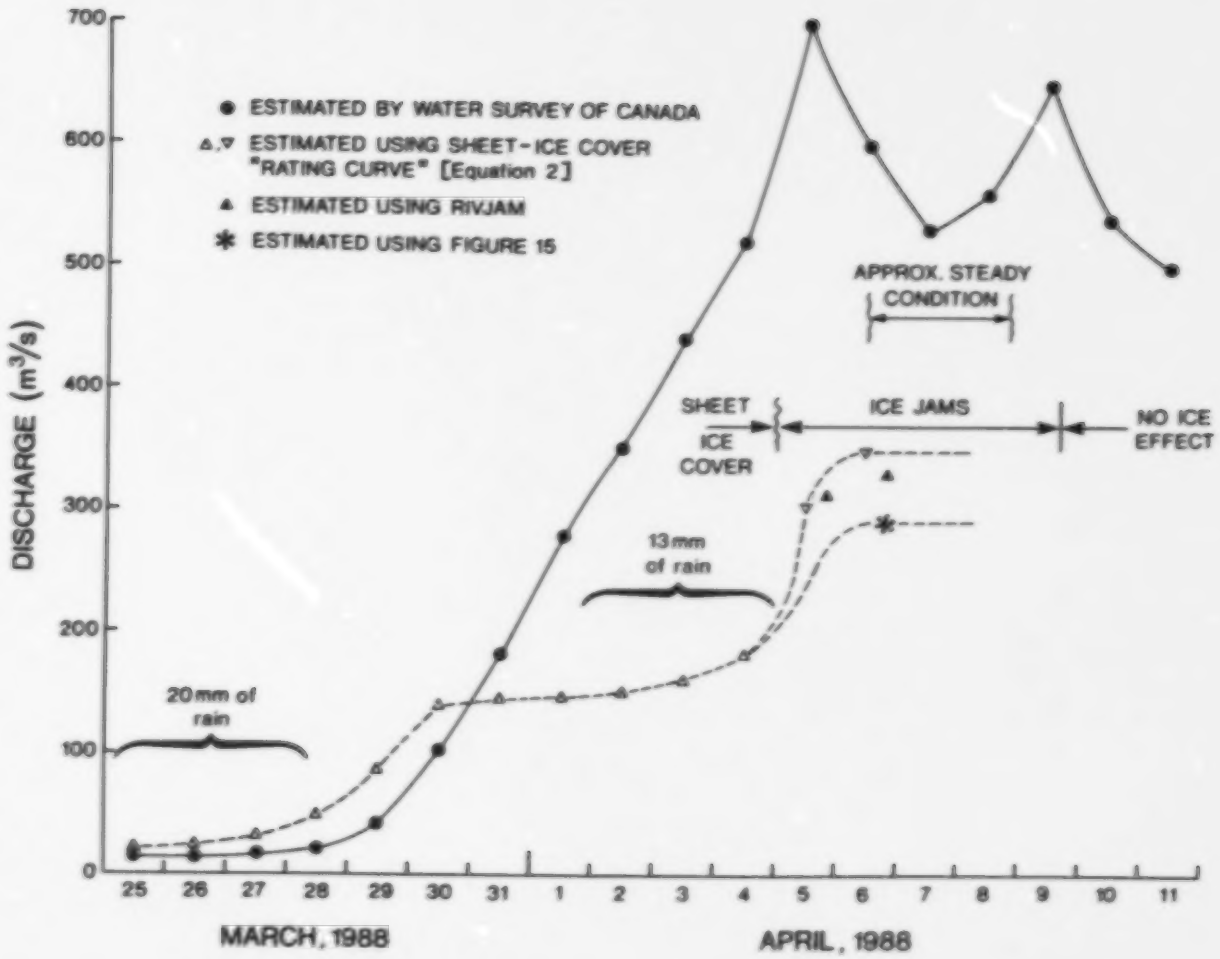


Fig. 14. Breakup discharge hydrographs synthesized by different methods. Rafting Ground Brook gauge.

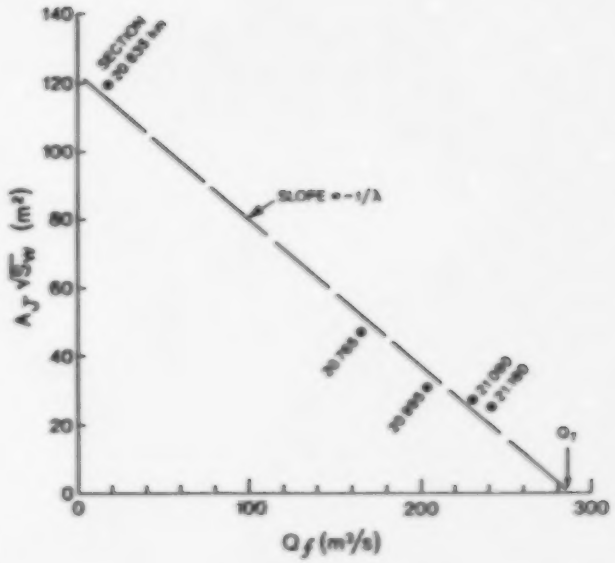


Fig. 15. Approximate determination of Q_T and λ, using measured water levels and shear wall heights near the toe of the jam.

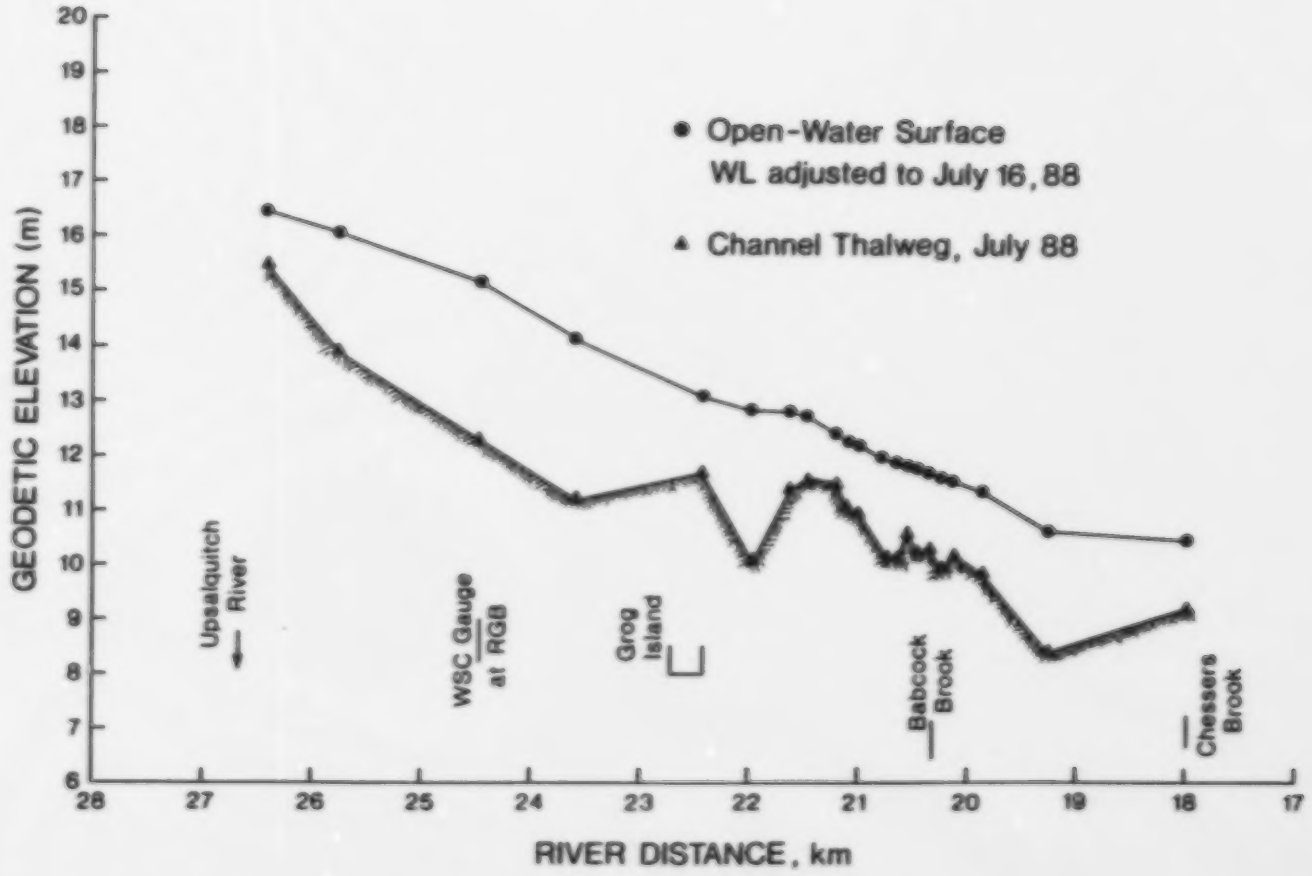


Fig. 16. Longitudinal profile of Restigouche River in part of the study reach.

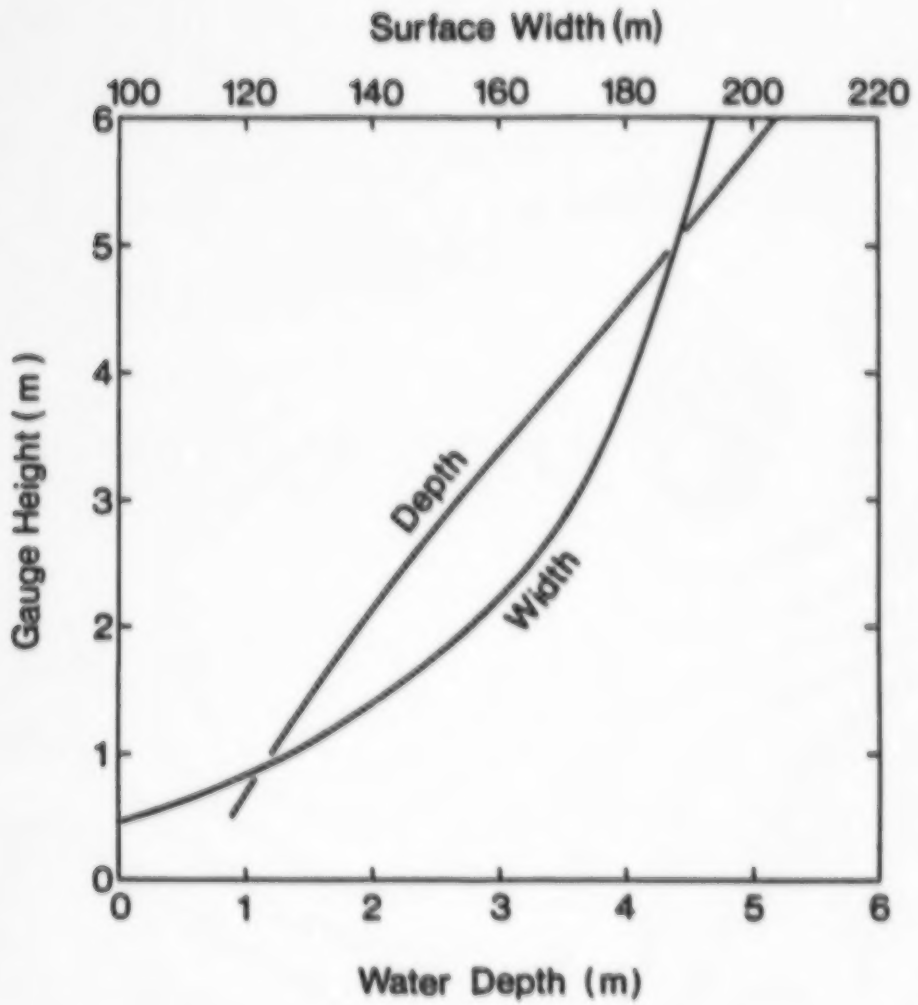


Fig. 17. Variations of reach-average flow depth and water surface width near Rafting Ground Brook; open water conditions.

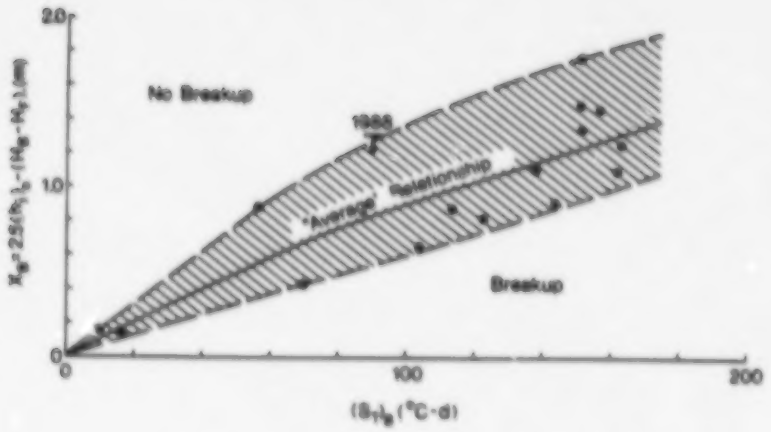


Fig. 18. Criterion to forecast the initiation of breakup, based on past records; comparison with 1988 results.

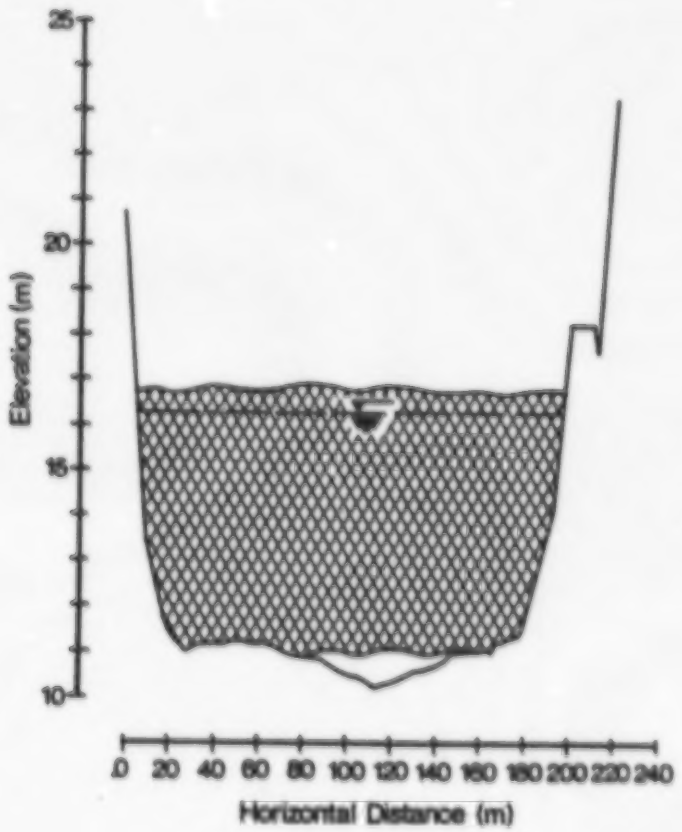


Fig. 19. River Cross-section at the toe of the jam, on April 6. Note extensive grounding.

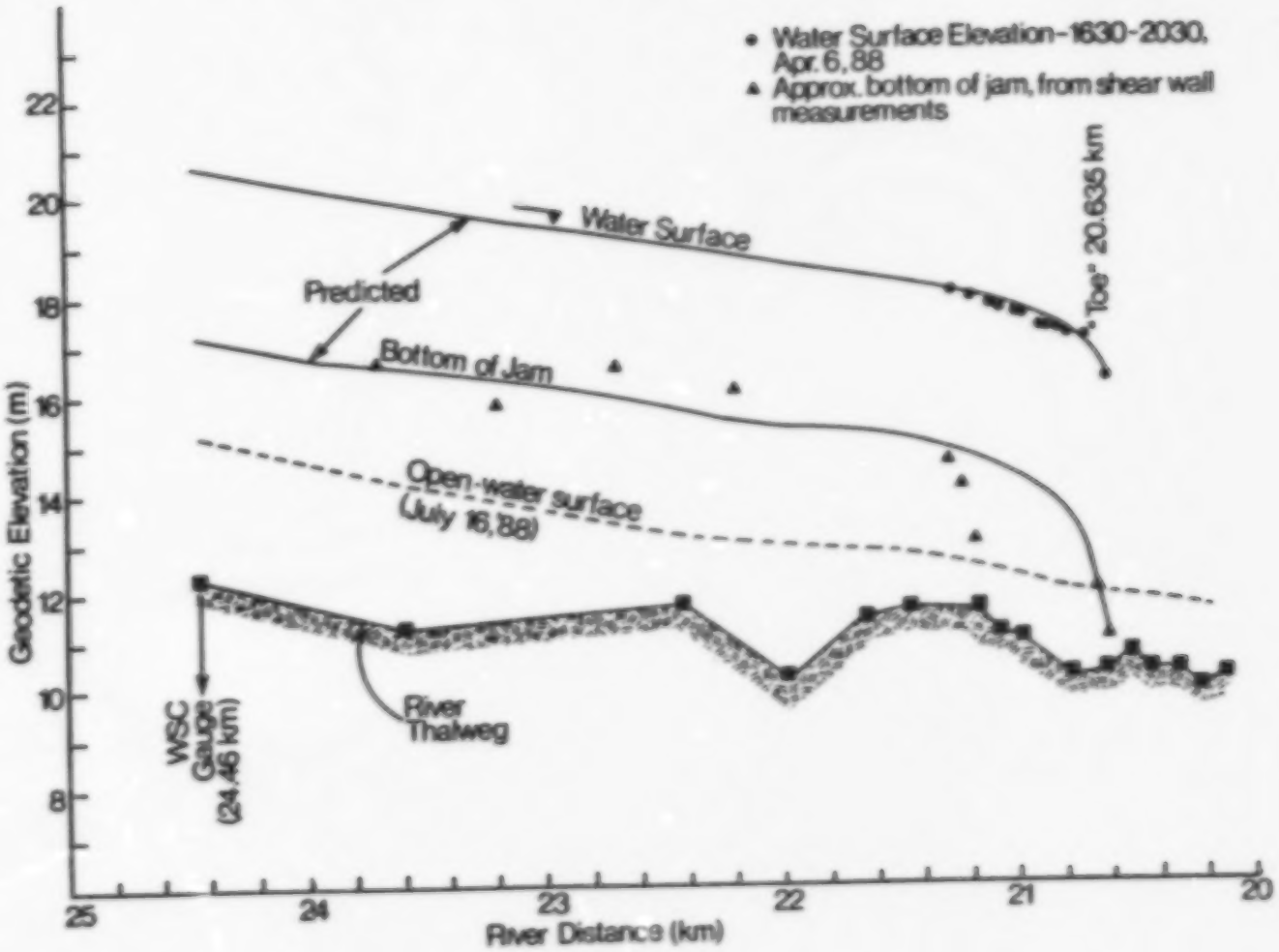


Fig. 20. Results of modelling using RIVJAM, for the conditions of April 6.

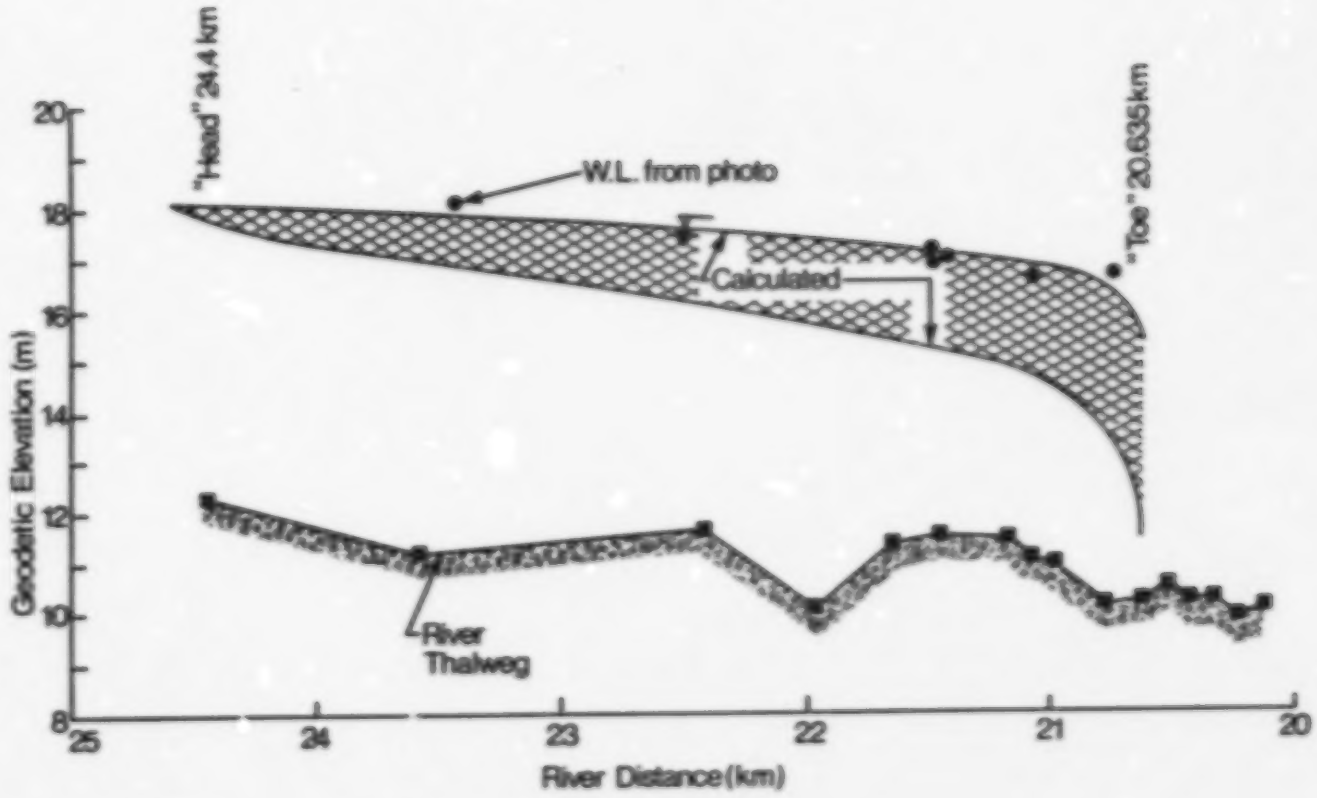


Fig. 21. Comparison between RIVJAM predictions and measurements for the short jam on April 5; the water levels are crude (from photos) but head location is predicted to within a river width.

PHOTOGRAPHS

Unless otherwise indicated, photographs refer to the Restigouche River.

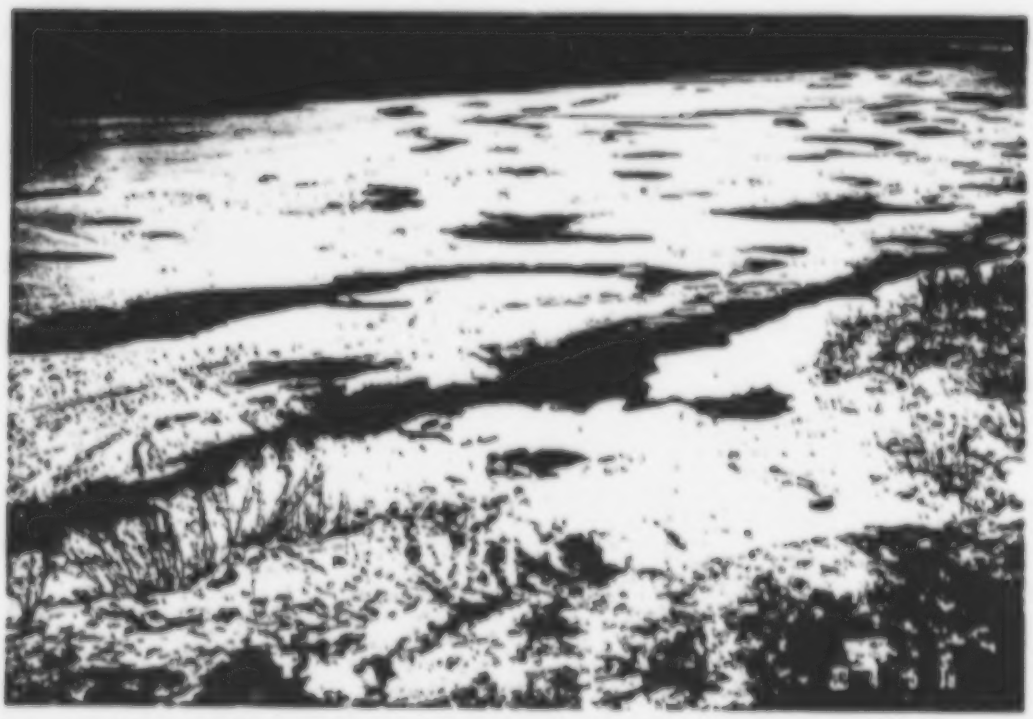
The following abbreviations are used in the captions.

→	Looking toward
bdg	bridge
Bk	Brook
d/s	downstream
LB	Left Bank (for an observer facing downstream)
mth	mouth
mtn	mountain
Mtp	Matapedia
NB	New Brunswick
R	River
RB	right bank (for an observer facing downstream)
Rd	Road
Ups	Upsalquitch
u/s	upstream

1. April 5, 1040. Ice piled on LB of Ups. R. - 2.7 km u/s of Robinsonville bdg.

2. April 5, 1050. Flooding on LB of Ups R. - 1.2 km d/s of Robinsonville bdg.

3. April 5, 1045. → u/s and LB. Ups R. jam ~ 1.7 km d/s of Robinsonville bdg.



4. April 5, 1830. → LB, Restigouche R. Intact ice cover ~ 400 m u/s of Chessers Bk.

5. April 5, 1730. → LB. Ridged and intact ice sheets ~ 500 m below toe of jam.

6. April 5, 1800. → d/s from ~ 0.35 km d/s toe of jam (location ~ 20.3 km); ice piles/ridges.

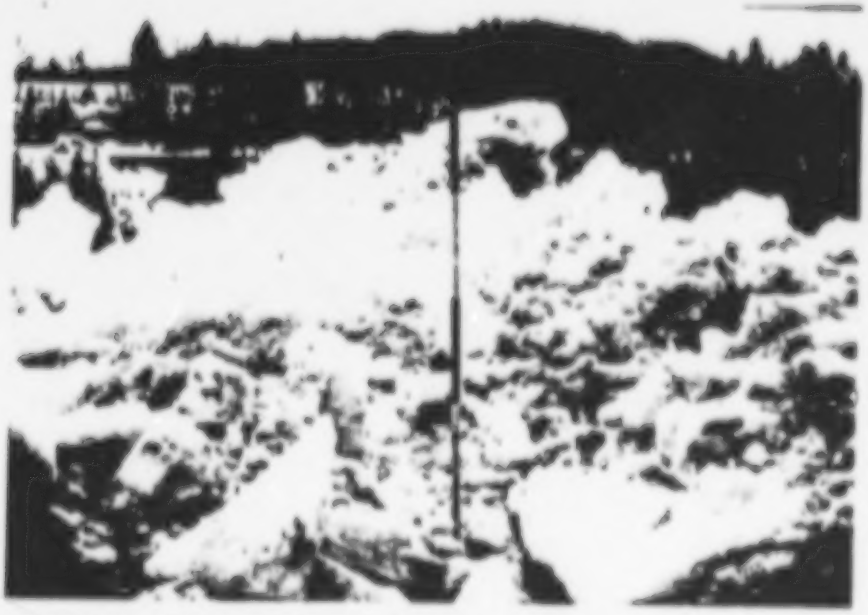
7. April 5, 1810. → LB just u/s toe of jam (location ~ 20.64 km)

8. April 5, 1810. → LB, just u/s toe; note ice pile.

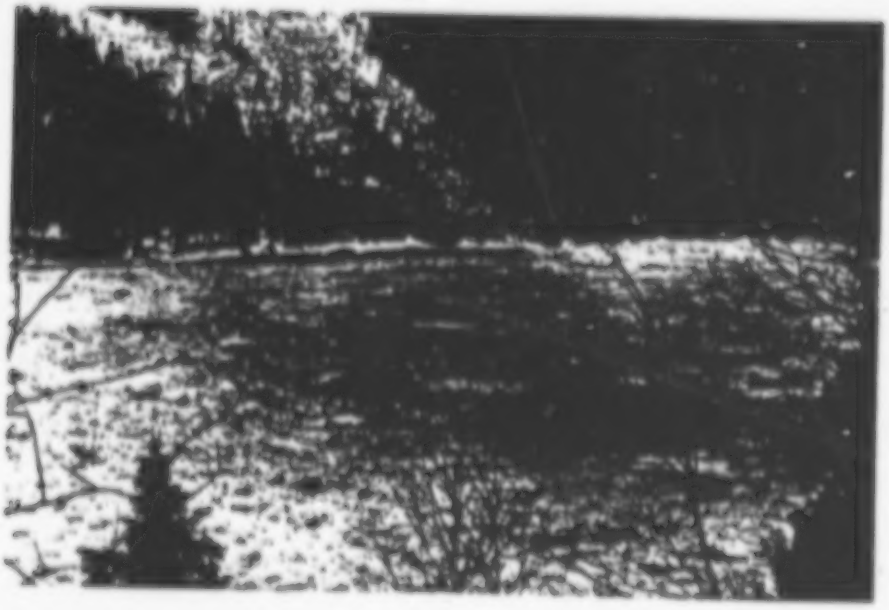
9. April 5, 1850. → u/s from ~ .6 km above toe of jam (location ~ 21.2 km). Note jam threatening road.

10. April 6, 0930. → LB at toe of jam. Note open lead near mid-stream.

11. April 6, 0830. → u/s; New Brunswick River Road covered with ice blocks (flooded farther u/s).



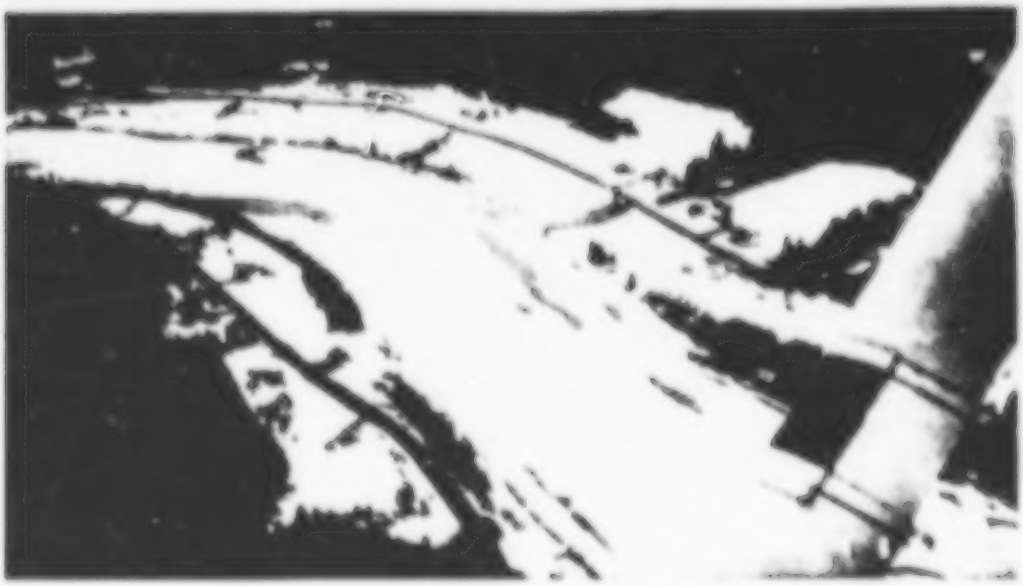
12. April 6, 0900. Ice pile on RB near toe of jam.



13. April 6, 1020. → RB, slightly d/s of flooded section of N.B. River Rd.

14. April 6, 1205. → u/s to Duncan and McBeath Islands (near Tide Head).

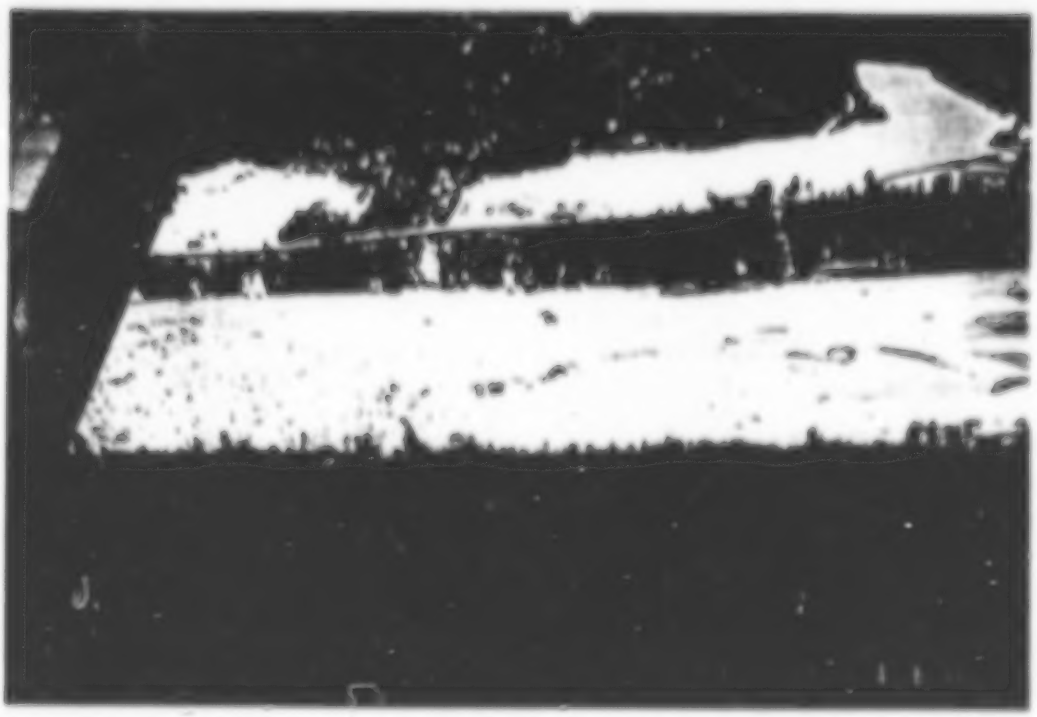
15. April 6, 1205. → u/s to Mtp. R. at confluence with Restigouche.



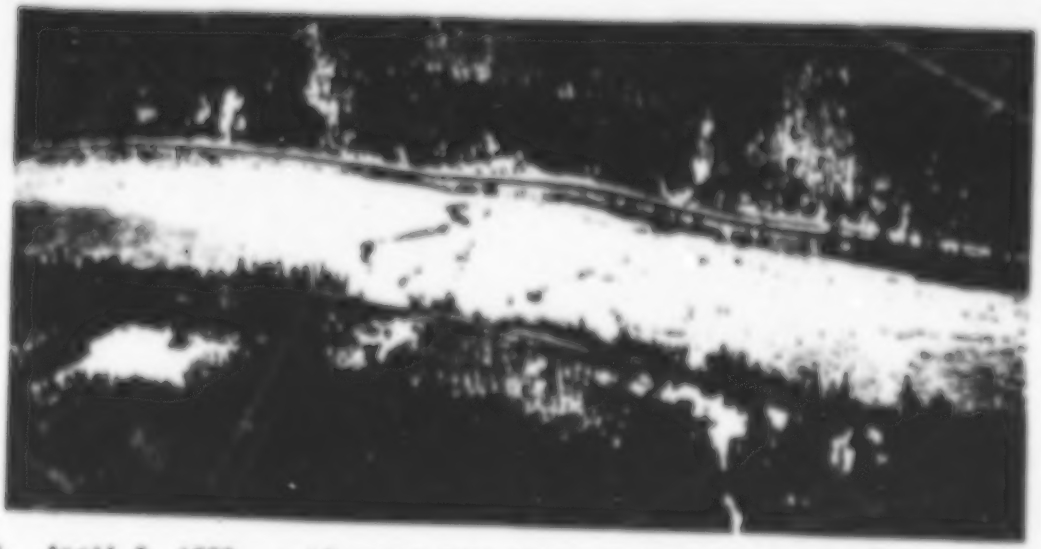
16. April 6, 1215. ◄ u/s near Chessers Bk. Note open leads in sheet ice cover.

17. April 6, 1215. ◄ LB, near Chessers Bk. Note leads and sheet ice cover.

18. April 6, 1215. - LB, slightly u/s of Ph.17.



19. April 6, 1215. - LB at toe of jam. Note small open lead in sheet ice cover at toe.



20. April 6, 1220. → LB, near Grog Island. Note sheet ice cover over grounded ice, extending ~ 2/3 of channed width.

21. April 6, 1220. → LB u/s, near Runnymede.

22. April 6, 1245. ← RB, slightly u/s of Ups R. mth. Ice over low section of road to Wyer's Bk.

23. April 6, 1245. ← RB. Flooded area u/s of Wyer's Bk.

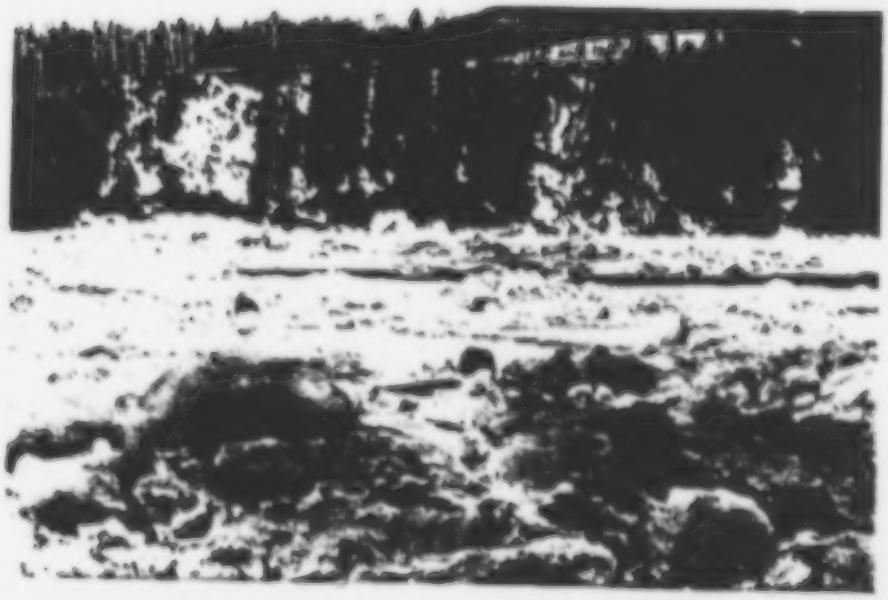
24. April 6, 1235. - RB; flooded area d/s of Brandy Bk.

25. April 6, 1225. - u/s to head of jam, ~ 2.3 km u/s of Brandy Bk.

26. April 6, 1210, Mtp. R. → u/s and LB near Legacé Creek. Note preferential melting under "active" flow channels.

27. April 7, 1020. Restigouche R. → RB at toe of jam. Note enlargement of lead since previous day.

28. April 7, 1030. → u/s; Quebec River Rd. flooded and closed.



29. April 8, 0923. → LB at toe of jam. Note enlarged lead and ice rubble emerging well above water surface, suggesting that rubble was grounded.

30. April 8, 1030. → u/s to toe of jam.

31. April 8, 1800. Ups. R. → d/s. shear wall - 1.8 m high.

32. April 9, 0900. → LB at toe of jam. Open lead has extended into jam. Ice fragments are carried in lead. Water "boils" visible.

33. April 9, 0830. → LB and u/s. Just below location of Ph. 32.

34. April 9, 0940. → d/s, below toe of jam. Note ice "mounds" caused by water level drop.

35. April 9, 0920. → u/s, ~ 0.7 km u/s of toe of jam. N.B. River Rd. flooded.

36. April 9, 0945. → LB, from (former) toe. Rubble moving in lead as jam releases.

37. April 9, 0945. → u/s, from (former) toe. Release of ice jam. Rubble and sheet ice in motion.

38. April 9, 1430. → RB at (former) toe. Note high shear walls.

39. April 9, 1435. → RB at Grog Island. Note shear walls.

40. April 11, 1500. → LB at former toe site. Note shape of shear wall produced by rapidly increasing jam thickness u/s of toe, and gradually decreasing d/s.

41. April 11, 1500. → LB, at Grog. Island. Note stranded ice and compare with Ph.20.

42. April 9, 1600. Mtp. R. → RB to shear wall (frazil/ice blocks), at ~ 20 km u/s of St. Alexis bdg.

43. April 11, 1455. Mtp. R. Confluence. All clear. Compare with Ph.15.

44. April 11, 1825. ← d/s near Wyer's Bk. Note shear wall on Greens Island.

45. April 11, 1800. ← d/s near Wyer's Bk. Road damaged by flooding.

46. April 11, 2010. - u/s. Ice jam in minor channel to the right of Duffs Island.